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The AR6A Single-Sideband Microwave Radio System:

System Design and Performance

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This paper describes the overall architecture of the first long-distance microwave telephone transmission system to use Single-Sideband Amplitude Modulation in the microwave transmission path. Compared witb commonly used frequency modulation systems, the AR6A Single-Sideband Microwave Radio System more than doubles the number of telephone circuits that can be carried per unit of microwave bandwidth. Included in the description are the system design model, performance objectives, and the allocation of performance impairments. Also discussed are the computer-controlled automated maintenance features and the results of laboratory and field tests.

I. GENERAL DESCRIPTION

1.1 Introduction

The AR6A† System is the first long-haul microwave transmission facility to employ Single-Sideband Amplitude Modulation (SSBAM)‡ in the microwave transmission path. To fully exploit this alternative to the widely used frequency-modulation (FM) system, it has been necessary to develop for SSBAM new subsystems to accomplish the

* Bell Laboratories.

† Amplitude Modulation Radio at 6 GHz for the initial (A) version of the system.

‡ Acronyms and abbreviations used in the text and figures of this paper are defined at the back of this *Journal.*

functions commonly associated with an integrated microwave transmission facility. In this sense, the use of SSBAM affects not only tbe design of the transmitter-receiver (TR) equipment but all ancillary equipment as well.

Broadly speaking, the main functional elements of tbe system are fairly conventional, but a number of SSBAM's basic requirements have had a major impact on the AR6A System design. The first and most obvious of these is the high level of linearity needed in many of the transmission elements to control intermodulation distortion. Although the most taxing task was making the transmitting traveling-wave-tube amplifier meet overall system linearity objectives, the intermodulation performance of many other elements required careful scrutiny and improvement. Frequently, the more stringent linearity requirements have been associated with higher quiescent current for transistors and, in general, with increased power requirements relative to comparable elements in an FM system. Nevertbeless, when power requirements are normalized to a per-circuit or a per-mastergroup basis, power utilization efficiencies are very competitive.

In addition, the direct dependence of signal amplitude response on the response of the transmission medium is particularly stressing during multipath fading. This requires adding a capability for dynamic amplitude equalization. Design of the necessary adaptive equalizers required an extensive experimental effort aimed at quantitatively describing tbe statistics for and understanding the effects of multipath fading on channel amplitude shape. The dynamic dispersive channel resulting from multipath fading required not only adaptive equalizers but also the use of space diversity.

Unlike FM, in which demodulation is performed relative to a transmitted FM carrier, accumulated frequency shifts due to multiple modulation and remodulation at repeaters must be removed. This adds to the complexity of the terminal multiplex equipment that performs the frequency-correction function.

Finally, successful transmission of SSBAM requires new maintenance and equalization considerations. In FM systems, minor amounts of transmission slope and absolute amplitude cbanges do not greatly affect the quality of the recovered baseband signal. The greater sensitivity of SSBAM to these effects, particularly their potentially cumulative nature, requires much closer control of equalization and absolute amplitude levels. These considerations, combined with the trend towards centralized operational support systems, resulted in the integrated development of a minicomputer-based Transmission Surveillance System—Radio (TSS-R) with associated trouble isolation and stress test features.

During development, effort was initially focused on applications

employing frequency-diversity protection, the most commonly used system arrangement. This work was later supplemented by the development of hot-standby and space-diversity arrangements for applications where lower cross-sectional growth rates preclude the use of frequency-diversity protection.

Because of the many new system features, AR6A underwent an early but limited field trial between Ashburnham and Wendell, Massachusetts, in the period October 1977 to July 1978. This two-hop installation provided valuable initial field experience prior to a more comprehensive field evaluation between Hillsboro and Windsor, Missouri. The Missouri evaluation involving a six-hop radio section with frequency- and space-diversity protection switching encompassed the period from April 1979 to June 1980. The evaluation of hot-standby arrangements was performed later on a two-hop section between Colorado Springs and Cedarwood, Colorado. The shipment of standard AR6A equipment began in June 1980; first commercial service was placed on the AR6A route between Hillsboro, Missouri, and La Cygne, Kansas, in January 1981.

The following paragraphs are devoted to an overview of the AR6A System using the block diagram of Fig. 1. The figure and discussion relate to a system configuration using frequency-diversity protection switching which, besides being the most common application, will provide a satisfactory medium for describing the main features of the system.

1.2 Multiplex

1.2.1 Mastergroup translators

The AR6A System interfaces with the standard Bell System analog multiplex hierarchy at the basic U600 mastergroup level. This is also the highest level in the multiplex hierarchy at which AR6A can be interconnected to other broadband transmission facilities. The U600 mastergroup contains 600 4-kHz circuits in the frequency band 564 to 3084 kHz. Figure 1 illustrates how the basic mastergroup is delivered from the Mastergroup Distributing Frame (MGDF) to the first frequency translation step provided by the Mastergroup Translator, Type B (MGTB). Five MGTBs translate and frequency multiplex five separate mastergroup signals into adjacent positions in a multimastergroup band extending from 8.628 to 21.900 MHz. Witb a fixed intermastergroup spacing of 168 kHz, the tight packing provided by the MGTB is an important factor in being able to place two multimastergroups (ten mastergroups) in each 30-MHz broadband radio channel.

In addition to modulation and demodulation, the MGTB modems supply the 2840-kHz mastergroup pilot which is used in the receiving

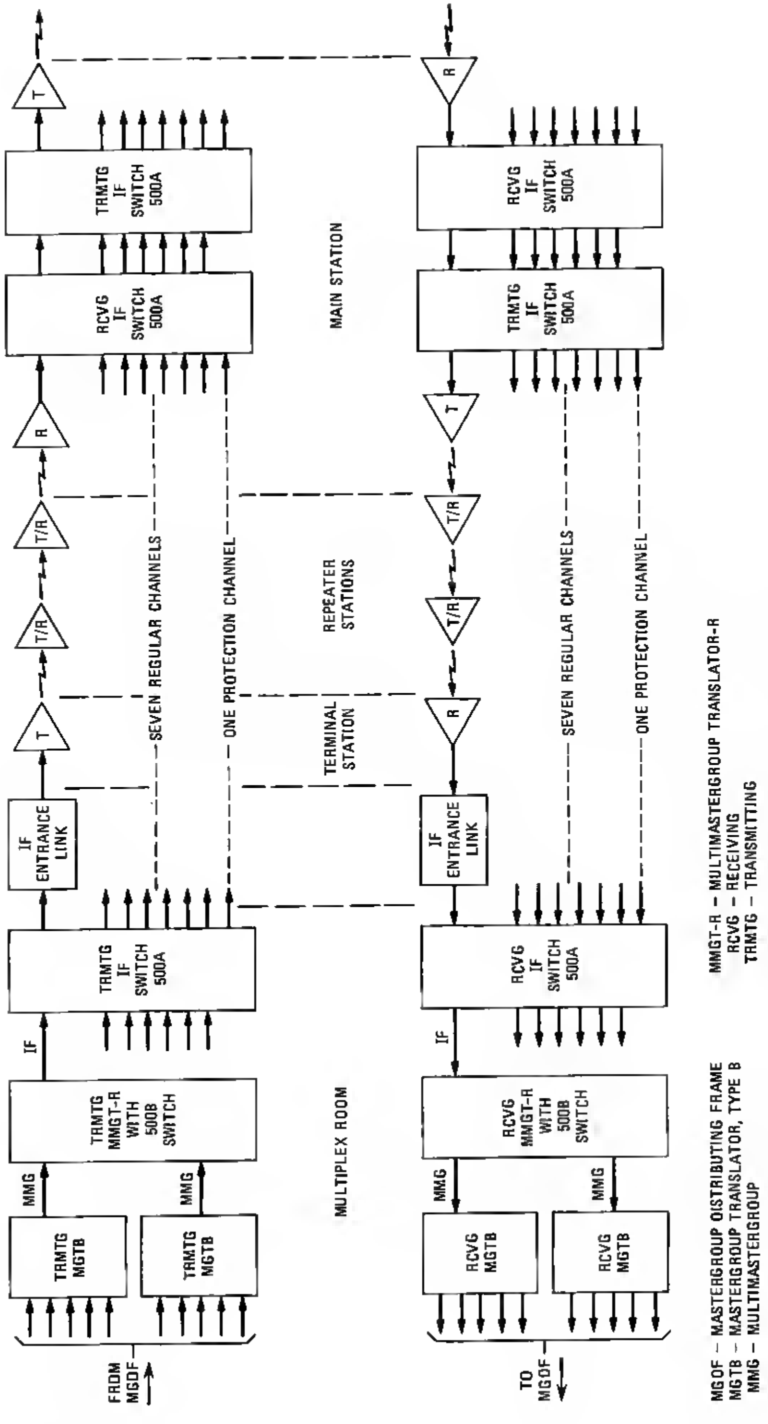

Fig. 1—Block diagram of AR6A System.

portion of the modem for gain regulation purposes. Other functions associated with the MGTB combining circuits are (1) means for inserting a 13.920-MHz multimastergroup continuity pilot for sectionalizing troubles, (2) a comb filter with narrowband band-stop sections which remove signals and noise from intermastergroup slots prior to the insertion of line pilots, and (3) test access points for TSS-R and other automated measuring facilities.

1.2.2 Multimastergroup translators

The Multimastergroup Translator—Radio (MMGT-R) performs the next modulation step by translating two multimastergroups into the intermediate frequency (IF) band centered at 74.13 MHz. The disposition of the multimastergroups and the previously described translation steps from basic mastergroup are illustrated in Fig. 2.

In the MMGT-R, the two multimastergroups are translated to IF by separate modulators with independent, unsynchronized, crystal-controlled local oscillators. On the receiving side, the demodulating carriers are supplied by Voltage-Controlled Oscillators (VCOs). Each VCO tracks the accumulated line frequency errors with a Phase-Locked Loop (PLL) to deliver a frequency-corrected multimastergroup signal at the receiving end of the terminal section. Essential to the frequency-correcting process is the addition of an intermastergroup recovery pilot to each multimastergroup signal before it is translated to IF. This pilot at 16.608 MHz is frequency locked to a 512-kHz synchronizing signal derived from the Bell System Reference Frequency (BSRF). In view of the recovery pilot's importance, the synchronizing source supplied to the MMGT-R is duplicated and automatically protected. At the output of the receiving MMGT-R, the demodulated recovery pilot is compared with a locally generated reference frequency to provide the PLL error signal for frequency correction. An important additional function of the receiving PLL is to reduce accumulated phase jitter on the radio line.

In addition to recovery pilots, the transmitting portion of the MMGT-R supplies three radio-line pilots from free-running crystal oscillators. When translated to IF these pilots are located near the center and band edges of the radio channel, as illustrated in Fig. 2. At radio receivers, the pilots provide a reference signal for Automatic Gain Control (AGC) and, in addition, provide information on channel amplitude shape for dynamic amplitude equalization. The radio pilots, recovery pilots, and multimastergroup pilots are each transmitted at a level of −10 dBm0.

1.2.3 Office master frequency supply

Carrier supplies for the Bell System analog multiplex hierarchy are

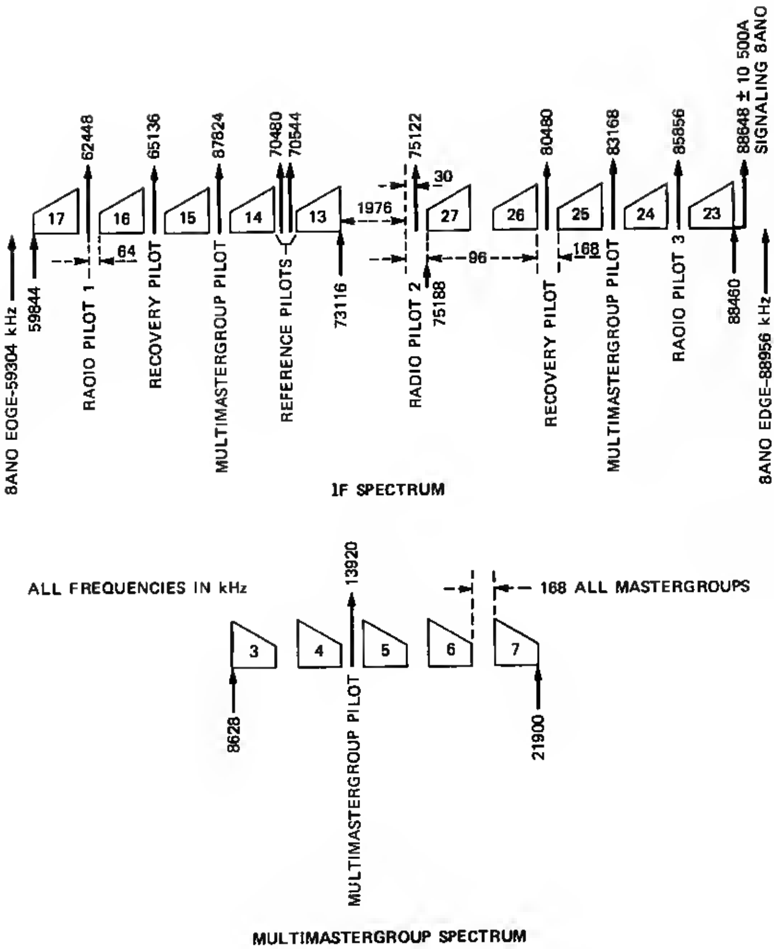

Fig. 2—Multimastergroup and IF spectrum.

locked to a 64- or 512-kHz synchronizing source derived from an office Primary Frequency Supply (PFS). The PFS is in turn synchronized to a signal with a frequency accuracy that is traceable within very narrow limits to that of the BSRF source at Hillsboro, Missouri. If the PFS temporarily loses its input synchronizing signal, the output frequency will suddenly change to the unit's natural or rest frequency. This frequency transient, although tolerable at lower levels in the multiplex hierarchy, was considered excessive in a synchronizing source for the AR6A recovery pilots. For this reason, a new Office Master Frequency Supply (OMFS) was developed which provides 64- and 512-kHz synchronizing signals that are quasi-frequency locked to the 2.048-MHz BSRF. With quasi-frequency lock, instead of being

synchronized to the incoming reference signal, the highly stable OMFS oscillators are free-running. Their frequency is compared with the reference frequency at intervals and smoothly updated if the error exceeds the prescribed threshold. If the reference frequency is temporarily lost, updating is inhibited and the oscillators continue to run at their most recently updated frequency. In this way the OMFS shields dependent multiplex equipment from transient effects on the synchronizing network.

1.2.4 Reference frequency transmission

The 2.048-MHz Bell System Reference Frequency must be available at all AR6A terminal stations for the purposes described in Section 1.2.3. The reference signal can be made available over a variety of transmission facilities, but there are instances where the only available transmission medium will be the AR6A System. To provide this capability, an optional reference frequency sending unit is available that inserts two pilots between MG13 and MG14 (Fig. 2) at a level of −15 dBm0. The pilot frequencies differ by 64 kHz with an accuracy determined by the sending end BSRF. At the receiving end of the terminal section, a reference frequency receiving unit recreates a BSRF at 2.048 MHz from the accurately defined 64-kHz difference frequency. In this way, reference frequency transmission accuracy is unaffected by inaccuracies in the multiple frequency translations experienced on the radio line. Sixty-four-kHz rather than a wider frequency separation was chosen to minimize transmission dispersion effects and to optimize pilot positions from the standpoint of noise and freedom from interaction with other system pilots. The sending and receiving frequency units are physically associated with the MMGT-R equipment.

1.3 The radio line

1.3.1 Entrance links

Figure 1 shows that the IF signal from the MMGT-R is fed to the radio transmitting equipment via the 500A Protection Switching System, which will be discussed in Section 1.4. Since the radio transmitters may be at some physical distance from the preceding multiplex equipment, provision must be made for handling trunk losses and associated transmission shapes. In some instances, the trunks may be so long that they require amplification, necessitating automatic protection of the active circuits. In the AR6A System, the 500A protection switching equipment is located near the MGTB and MMGT-R multiplex equipment. In this way, the trunks or entrance links become extensions of the radio line and may, therefore, share the 500A protection facilities.

For distances up to 600 feet, the entrance link trunks are passive

and are equalized to within 25 feet. Greater distances require amplification by amplifiers located in the TR bays for both the transmitting and receiving trunks. This provides for entrance link distances of up to 1200 feet using 728-type office coaxial cable. Entrance link distances up to 3600 feet can be accommodated with 0.375-inch coaxial cable.

1.3.2 Transmitter-receiver equipment

The heterodyne-type transmitter-receiver (TR) bays are designed for overbuilding on existing 4-GHz radio routes with an average repeater spacing of 25.6 miles. The nominal repeater gain is 61.7 dB with up-fade and down-fade ranges of 15 and 46 dB, respectively. The full-load transmitter output power is +24.6 dBm, reflecting an average power per 4-kHz message circuit of −19.6 dBm0.

The TR bay equipment is designed to permit field installation by technicians into existing bay frameworks. Tbis modular installation allows the bay frameworks to be installed and the station wiring to be done for all radio channels at one time. The TR modules are installed as required by the route traffic.

The transmitter uses IF predistortion to compensate for the nonlinearities of the up converter and the output traveling-wave-tube amplifier. Automatic gain control (AGC) at each receiver is based on maintaining the voltage average of the three pilots constant at the receiver output. In addition to AGC, the last receiver in eacb switch section is equipped with a dynamic amplitude equalizer.

A microwave preamplifier with a noise figure of approximately 3 dB is provided in the common receiving waveguide run on eacb polarization. If the hop length is less than 63 percent of nominal, the preamplifier is omitted.

To meet long-haul reliability objectives within the FCC-prescribed limit of only one frequency-diversity protection channel to serve up to seven service channels, it is estimated that approximately half the radio hops will require space diversity. The TR bay is, therefore, equipped with an optional space-diversity switch that is actuated by a 36-dB fade in any one of the three radio-line pilots.

In the event of a loss of received signal due to equipment trouble or other reasons, a pilot resupply signal is automatically inserted at the receiver output. In addition to supplying the three radio-line pilots, the resupply source provides a fourth pilot tbat is located in the center noise-monitoring slot of the 500A Protection Switching System. The channel with resupply is thereby marked noisy and unavailable for service. The pilot resupply signal at each station is provided from a common source and distribution network located in a radio support bay.

Networks in the IF shelf provide repeater bandpass shaping and

basic equalization for the nominal repeater transmission shape. Also, positions are provided for limited amounts of mop-up equalization for nonsystematic amplitude response variations.

Carrier supplies for up and down frequency conversion are provided by the TR bay microwave generator and its associated 252-MHz shift oscillator. To maintain pilot frequencies within the passband of the narrowband pilot pick-off filters at each repeater, the carrier frequencies must be accurate to better than one part in 10^7. This is achieved by locking the microwave generators and shift oscillators to a common submultiple frequency, 308.87354 kHz. This synchronizing frequency is distributed to each TR bay from a common synchronizing source located in the radio support bay. If the synchronizing signal fails, both the microwave generator and shift oscillator have memory circuits that maintain their frequencies at the most recently updated values. Subsequent drifting is at a rate that allows a one- to two-day window for repairing the failed synchronizing source.

1.3.3 Support bay

The support bay contains the Microwave Carrier Synchronization Supply (MCSS) and the pilot resupply source, along with associated distributing circuits. In addition, it provides power distribution, fusing, and alarm arrangements for up to eight microwave preamplifiers. The support bay is designed to supply up to 16 TR bays corresponding to one fully loaded route passing through a repeater station. In hot-standby applications, the radio support bay also contains the hot-standby control unit.

1.3.4 Antenna system

Since a common application of AR6A will involve overbuilding on existing 4-GHz radio routes, the system is designed around the currently used horn antenna system with associated system combining and separation networks. The space-diversity path should essentially duplicate the main path for a number of reasons, including the anticipated later application of space-diversity combining. With nominal tower heights and hop lengths, the combined section loss, waveguide losses, network losses, and antenna gains give a net overall nominal section loss of 61.7 dB.

1.4 Protection switching

1.4.1 500B Switching System

Since each MMGT-R carries 6000 message circuits, automatic transfer of the message load to a hot-standby protection unit is necessary for reliability and maintenance. The function is handled by the 500B System. One microprocessor-based controller oversees a 1 ×

14 protection arrangement for transmitting MMGT-Rs and a corresponding 1 × 14 protection arrangement for receiving MMGT-Rs. Since the protection function is local, multimastergroup translators from more than one route may be associated within the same 1 × 14 switching system.

In its automatic mode, a switch is initiated by a number of conditions including loss of the multimastergroup continuity pilot and loss of synchronization.

1.4.2 500A Protection Switching System

The 500A System provides frequency-diversity protection switching on the radio line. Switching sections may he up to ten hops in length and the microprocessor-hased control functions are located at the receiving end. The protection switching systems in the two directions of transmission are electrically independent.

Each protection channel can serve up to seven working channels. A frequency shift-keyed (FSK) tone transmitted over the oppositely directed radio channels signals between the receiving and head end of the switch section. The FSK tone is inserted at IF near the upper channel edge and is hlocked at the receiving end of each switch section.

Switch initiators monitor each of the three radio-line pilots as well as the noise in three narrowband slots adjacent to the pilots. This multiple monitoring causes more switching activity than the single-point monitoring on FM systems and is partly responsible for the approximately 50-percent space-diversity requirement for AR6A. In addition to protecting against frequency-selective fading, particularly on hops without space diversity, 500A protects against equipment failure and provides out-of-service access to the radio channels for maintenance purposes.

Maintenance access to a radio channel via a maintenance switch command to the 500A System is an essential element in the implementation of the centralized Transmission Surveillance System—Radio (TSS-R). Besides providing switched access to a channel at the transmit and receive ends of the switch section, the 500A control logic is responsihle for ensuring that accessing the channel is subordinate to maintaining service continuity. Even after out-of-service access to a channel is permitted, a preemption feature in the 500A logic will restore the channel to service automatically if this is necessary to prevent a service outage. When a channel is opened at the head end of the switch section to allow maintenance access, a fresh set of locally generated radio pilots must be inserted to provide proper control at subsequent radio receivers. These pilots are provided by the 500A System in the same way as resupply pilots are provided at repeaters.

1.5 Hot standby

On routes where the cross-sectional growth rate is low, current FCC rules do not permit the use of frequency-diversity protection channels. In these circumstances, protection against outage due to multipath fading is generally provided by using space diversity. To protect against radio equipment outage, space diversity must be supplemented with hot-standby radio equipment that is automatically switched into service when the need arises. This hot-standby configuration is available on AR6A although the number of applications is expected to be small compared to the frequency-diversity configuration.

Since radio repeaters are frequency-dependent, each working TR bay generally has a separate hot-standby bay. In this sense, hot-standby configurations are equipment-intensive. To ease this situation in AR6A, the east-west and west-east repeaters on a given radio channel are identical, including the frequency-dependent components. By providing appropriate switching and control arrangements, a common TR bay can be used to protect equipment for both directions of transmission. Main stations do not lend themselves to this reduced configuration and are, therefore, arranged with conventional one-for-one hot standby.

Hot-standby manual and automatic control functions at repeaters are provided by a microprocessor-based control unit. The same unit with a subset of features is used at main stations to control hot-standby switching of transmitters. Main station receivers are protected by the 501A Protection Switching System, which also has a double feed to the regular and hot-standby transmitters. In addition to providing noise and pilot-level monitoring with 500A-type initiators, the 501A System also enables the TSS-R System to monitor in service.

On a hot-standby route, each repeater has its own protection against equipment outage and multipath fading. There is, therefore, no natural equivalent to the multihop switch section of the frequency-diversity configuration. However, since hot-standby routes will often be converted to frequency diversity when growth permits, main station TR bay and waveguide configurations are recommended at those stations which at a later time may become switching or main stations. Since the main station configuration implies the use of the 501A switch with surveillance access, this sectionalizing of hot-standby routes into surveillance sections subdivides the route naturally for purposes of dynamic equalization, transmission monitoring, and trouble isolation. The interface transmission levels on the 501A System are identical to those on the 500A switch to further simplify the transition from hot standby to frequency diversity.

1.6 Maintenance

Compared with FM systems, the somewhat less rugged modulation

technique and the higher capacity of tbe AR6A System have emphasized the need for careful maintenance planning in the overall system design. Supplementing these considerations is the ongoing trend towards a demand maintenance scenario, improved trouble isolation procedures, and centralized transmission surveillance capabilities.

On AR6A, status reporting and command functions are handled conventionally utilizing the C1 or E2 systems in conjunction with the Surveillance and Control of Transmission Systems (SCOTS) or Telecommunication Alarm Surveillance and Control (TASC) central processors. However, in the 500A-to-E2 interface, which can involve a sizeable number of wire pairs, optional arrangements have been developed to provide a serial interface with only two wired pairs. This feature capitalizes on the 500A microprocessor that can communicate serially to microprocessor-based alarm remotes such as E2A.

For trouble-isolation purposes, a significant new feature is the ability to break the transmission path and insert resupply pilots at any selected station by remote command. This is supplemented by tbe capability to remotely modify the resupply signal to perform a variety of stress tests. With this feature, in conjunction with a measuring capability at the receiving end of a switch section, a variety of transmission troubles can be localized by making out-of-service measurements on successively shortened portions of the switch section. Of course, these capabilities must be circumscribed with protections against service interruption and loss of the 500A preemption feature. These matters are discussed more fully in Section 4.9.

Another important new maintenance feature is the Transmission Surveillance System—Radio (TSS-R). This system uses programmable measuring, signal source, and access equipment at radio main stations that are under the control of a local microprocessor. This microprocessor is, in turn, accessible and controlled via the Direct Distance Dialing (DDD) network from a central minicomputer. Data link dial-up and communication protocol, measuring, evaluation, and reporting routines residing in the central software provide for a variety of switch section transmission measurements that can be made either on an in-service or out-of-service basis. Furthermore, by allowing the TSS-R central minicomputer to talk to a SCOTS or TASC central, the trouble-isolation and stress test features described in the preceding paragraph can be integrated into automated programmable procedures. It should again be noted that access to a radio channel for in-service or out-of-service measurements is subject to approval by the 500A System control logic. It is anticipated that five TSS-R centrals will be able to cover all AR6A routes in the continental United States.

With respect to equipment maintenance, test equipment is, in general, conventional. However, transmitter linearization and precise

frequency adjustment of the MCSS require some special test equipment, which is described in a companion paper.[1]

II. PERFORMANCE OBJECTIVES

2.1 Noise

The 4000-mile, voice-circuit noise objective is 40 dBrnc0 under standard (free-space) propagation conditions. Attaining this level of performance requires state-of-the-art designs for many devices in the system and the recognition that the current per-circuit average power in the telephone network is lower than previous designs had assumed. The per-circuit average power used in the system design is −19.6 dBm0. This level has been found to be representative of both radio trunks[2] and the telephone network as a whole.[3] With the current increase in the use of common channel interoffice signaling, it is expected that this average power will decrease slightly.

2.2 Amplitude equalization

2.2.1 Static equalization

The static amplitude equalization objective requires the amplitude shape developed across a mastergroup to be not greater than ±3 dB in 4000 miles. This limit is established to be within the available correction range of regulators in the receiving multiplex equipment. Typical regulators have a ±6 dB range and ±3 dB is chosen as the allocation for the radio system. A supplementary objective of ±0.5 dB is established for the total misalignment within a radio channel in any given switch section. This limit prevents excessive errors in voiceband data systems during frequency-diversity switching between the regular and protection radio channels.

2.2.2 Dynamic equalization

As a result of the time-variant nature of propagation over typical microwave radio paths, an objective for time-variant signal amplitude is established. The objective is that for a 4000-mile circuit, tbe amplitude error should be less than ±2 dB for 99.9 percent of tbe time. The ±2 dB limit is chosen since variations exceeding this level can cause errors in some voiceband data systems. Ordinary telephone service is more tolerant of this impairment.

2.3 Tone interference

The tone interference objective uses the ratio of spurious tone power to background (masking) noise power in a voice circuit as the measure of impairment. This measure is directly related to the annoying effect perceived by the customer. It also has the desirable feature of being

straightforward to administer in a large system, since each subsystem produces its own background noise and the tone requirements for the individual subsystems follow directly. The objective is stated on a percent of time basis as follows. The tone-to-noise power ratio should be less than: (1) −10 dB for 99 percent of the time, (2) 0 dB for 99.9 percent of the time, and (3) 2 dB 100 percent of the time.

In applying the tone objective to the radio line, it is found that on long routes the radio-line noise is dominated by the noise of a faded hop for more than 1 percent of the time. For tone mechanisms that increase with fading, the receiver thermal noise is then used as the background noise for the per-repeater tone objective. For tones that do not increase in level, the total radio repeater noise is used.

2.4 Crosstalk

Separate objectives have been established for intelligible and unintelligible crosstalk. The objective for the former is that the crosstalk index should be less than 0.5 percent. This corresponds approximately to a probability of 0.005 of hearing one or more syllables of intelligible crosstalk during an average duration call. The unintelligible crosstalk or babble objective is stated in terms of a babble-to-noise power ratio that must be met during certain percentages of the time. The babble-to-noise ratio must be less than −10 dB 99 percent of the time and less than 7 dB 100 percent of the time.

2.5 Phase jitter

The objective for phase jitter (unwanted phase modulation) in 4000-mile circuits is 8 degrees peak to peak. The objective applies to jitter with either discrete or continuous frequency components. The jitter is measured by a standard jitter indicator[4] that is sensitive to spectral components in the range of 20 through 300 Hz.

2.6 Reliability

The reliability objective for a 4000-mile circuit is that it should be available for two-way service with noise less than 55 dBrnc0 for 99.98 percent of the time. This objective is apportioned among three sources of outage as follows: (1) equipment outage, 0.005 percent; (2) flat fading, 0.005 percent; and (3) selective fading, 0.010 percent. To meet the equipment reliability objective, the system design requires either frequency-diversity or hot-standby protection switching. The application of space-diversity antennas to meet the selective fading objective is discussed in Section 4.7.

III. SYSTEM MODEL AND PERFORMANCE ALLOCATIONS

3.1 The 4000-mile system model

As a basis for calculating the expected performance of the radio

system, a 4000-mile system model is used. The model is derived from the characteristics of the existing Bell System microwave radio network. The network has a mean hop length of approximately 25.6 miles, resulting in 156 hops in 4000 miles. The network root-mean-square (rms) hop length is 27.1 miles and this latter value is used for thermal noise and received signal-level calculations. The section loss corresponding to the rms hop is assumed to he 61.7 dB with typical antenna systems. This value includes all losses and gains from the output monitor-shutter in the transmitter to the input of either the receiving bay lineup or the microwave preamplifier if it is installed. The 4000-mile route is assumed to have 52 switch sections averaging three hops in length. Multiplex and terminal equipment is assumed to be located at nine intermediate points on the route. A 4000-mile circuit is thus assumed to pass through ten sets of MMGT-R and MGTB equipment. In addition, the circuit is assumed to pass through a total of nine sets of supergroup multiplex, six sets of group multiplex, and three sets of channel banks. The mastergroups within the spectrum of a radio channel are assumed to be interchanged or frogged every 400 miles for six of the terminal sections and 800 miles for two of the terminal sections.

3.2 Performance allocations

3.2.1 Noise

Figure 3 shows the noise allocation for the system. The terminal equipment allocation results from assuming two-thirds of the multiplex equipment helow mastergroup level is LMX-2 and one-third is LMX-3. This mix is representative of the network during the initial introduction of the system. Thermal and intermodulation noise are the primary contributors to the terminal equipment and protection switching allocations.

Four major interference mechanisms contrihute to the RF interference allocation. Cochannel same-route exposures occur at the nine intermediate multiplex stations in the system model. At other stations, the same-route mechanism produces talker echo as a result of the system frequency stahility and Radio Frequency (RF) channel plan. At stations with intersecting routes, cochannel junction interference occurs. The allocation assumes a mixture of AR6A and FM intersecting routes that will exist during the initial introduction of AR6A into the radio network. The third mechanism is cochannel interference from other terrestrial radio systems. All stations in the system model are subject to this interference. The final mechanism is cochannel interference from geostationary satellite earth stations. An allocation of 30 dBrnc0 has been set for this source.

The major contributors to the radio repeater allocation are thermal

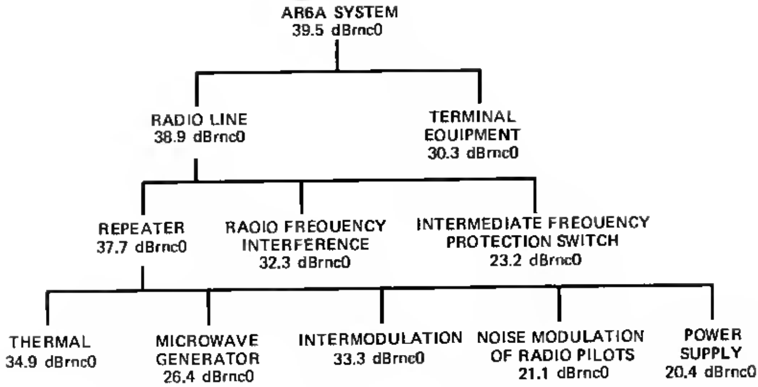

Fig. 3—AR6A noise allocation.

and intermodulation noise. The relative levels of these contributors result from an optimization of the overall system noise with respect to transmitter output power. During the development process, the allocations for these sources were lowered as a result of the use of the microwave preamplifier and the lower per-circuit average power of −19.6 dBm0.

The microwave generator allocation results from phase noise sidebands produced by the generator. In the modulation processes that use the generator output, these sidebands are convolved with the signal and produce an unwanted additive noise. In the system design, this noise is minimized at repeater stations by using one microwave generator to down-convert and up-convert each channel. The noise introduced in the two conversions nearly cancels. The predominant contributors to the allocation are the separate microwave generators used at main stations.

Since the system gain is controlled by the detected level of the three radio pilots, any spurious energy entering the passbands of the detection circuitry causes unwanted amplitude modulation of the signal. The modulation results in additive noise. The allocation for noise modulation of the radio pilots results from accumulation within a multiplex section of radio-line thermal and other noise near the radio pilots. At multiplex locations, the noise from previous paths, within the detection circuitry bandwidth, is removed and new pilots are inserted.

The power supply allocation results from a similar process. Ripple or other nonuniformity of the power supply voltages results in unwanted modulation of the signal. That portion of the modulation energy that is outside of the radio pilot detection circuitry bandwidth remains on the signal and produces noise. The predominant contributor to this allocation is the traveling-wave-tube (TWT) power supply.

3.2.2 Amplitude equalization

The static equalization objective for mastergroup shape is allocated among: (1) the residual shape of IF and MMG trunks, (2) the residual shape of an equalized radio bay, (3) echoes in the antenna and waveguide systems, (4) signal leakage through the space-diversity switch, and (5) tertiary interference. The predominant shape component is slope. The slopes introduced by all of the above sources are random and contribute to an estimated rms slope of 1.21 dB in 4000 miles. The slope distribution is approximately normal and the probability of exceeding a slope of 3 dB is then 1.3 percent. This probability is sufficiently small to satisfy the intent of the objective.

3.2.3 Crosstalk

The main sources of crosstalk in AR6A are interference exposures at junction stations and multiplex locations. The type of crosstalk produced by these exposures depends on the relative frequency stability of the interfering and desired signals. The calculated probabilities for the interference exposures producing intelligible crosstalk and babble are 0.45 and 0.55, respectively. Calculations using interference coupling levels typical of the radio network result in a crosstalk index of 0.12 percent for 4000-mile routes. The calculated probability of exceeding a −10 dB babble-to-noise ratio is 0.32 percent for 4000-mile routes. The remainder of the crosstalk and babble objectives are allocated to mechanisms producing discrete-frequency incidental modulation in the radio line.

IV. DESIGN ASPECTS

4.1 Frequency plan

4.1.1 Channel assignments

The AR6A System uses the standard 6-GHz frequency plan, which is shown in Fig. 4. This plan permits eight channels in each direction of transmission, which are designated the same as in the TH System: 11 through 18 in the lower portion of the frequency band and 21 through 28 in the upper portion of the frequency band. This plan places the receivers in one-half of the band and the transmitters in the other half. A station using the frequency plan shown in Fig. 4 is called a "low-high" station, because the receive channels are in the low-frequency portion of the band and the transmit channels are in the high-frequency portion of the band. Adjacent stations will be "high-low" stations. The microwave carrier frequencies, which are used in the receiver and transmitter modulators, are also shown in the figure, along with the channels served.

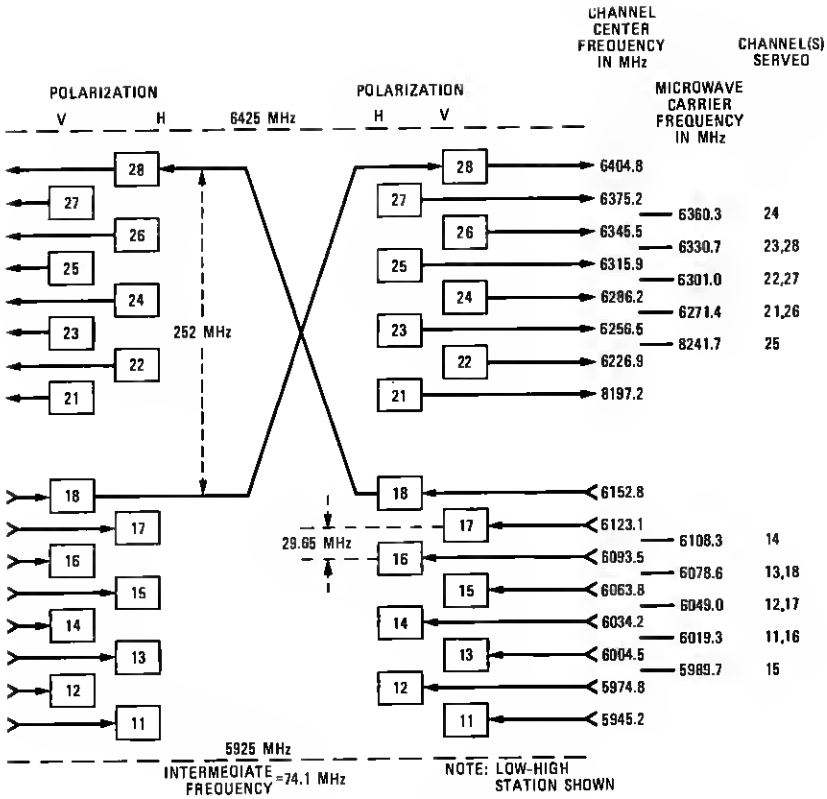

Fig. 4—AR6A frequency plan.

4.1.2 Choice of IF

An IF band centered at a frequency that is an odd multiple of half the channel separation is the best choice for minimizing the effects of microwave carrier leakages. With this choice of IF center frequency, these leakages appear at the edge between two channels and do not need as much suppression as they would if they fell inside a channel. On this basis the best IF center frequency for the 6-GHz frequency plan is 74.12965 MHz (usually referred to as 74.1 MHz). In addition to the advantage of controlling the effect of the microwave carrier leakages, a 74.1-MHz center frequency permits a reduction from 16 to 10 of the microwave carrier and filter codes needed, since some microwave carrier frequencies can be used for two channels by using upper and lower sideband modulators. These design factors favor the choice of 74.1 MHz. Consideration was given to using a center frequency of 70.0 MHz, which is used in the TH-3 and TD Radio Systems. This choice would permit the direct IF interconnection of FM systems

onto an AR6A radio channel. The ability to handle both AM and FM signals would have excessively complicated the AR6A design; therefore, an IF center frequency of 74.1 MHz was used.

4.1.3 IF band utilization

At both IF and microwave frequencies, the SSBAM signal with suppressed carrier occupies no additional bandwidth over the original baseband signal. Thus, mastergroups can be translated into the channel bandwidth with a spacing determined by the filtering requirements needed for separation when shifted back to baseband. Carrier systems previously used a frequency spacing between mastergroups of approximately 4 percent of the frequency, where the mastergroup was to be located based on the desire to separate mastergroups (block and branch) at the multimastergroup level. The use of mastergroup translators makes it more convenient and economical to make these rearrangements at the basic mastergroup level, which permits the use of a fixed frequency separation at the multimastergroup level. Improvements in filter performance have made it possible to form the MMG spectrum with only 168-kHz spacing between mastergroups. The number of mastergroups that can be placed in the radio channel bandwidth is constrained by cochannel interference from FM systems. Clearly, the center of the channel, which may contain interfering FM carriers, cannot be used, and further allowance must be made for the close-in sidebands of the FM signal since these are strong enough to cause serious interference into AR6A voice circuits. The situation for TH-3 is shown in Fig. 5. Consequently, a center gap of 2.072 MHz has been provided which, with frogging of the mastergroups, keeps interference at an acceptable level, and achieves a loading of ten mastergroups in the 29.65-MHz channel bandwidth. The addition of pilot tones in the gaps between mastergroups for regulation and control purposes completes the IF spectrum as shown in Fig. 2.

4.2 Frequency stabilization

4.2.1 Need for stabilization

An important aspect of the system design is the required frequency stability along a radio route. The radio pilots, which are transmitted as part of the IF spectrum, must be centered in their respective pick-off filters in each receiver. For best operation, the pilots should be within ± 2 kHz of their nominal frequencies. The necessary frequency accuracy is achieved by locking the microwave generators and shift oscillators at each station to a high-stability synchronization oscillator located in each station. This will stabilize both the microwave and the IF frequencies of the system.

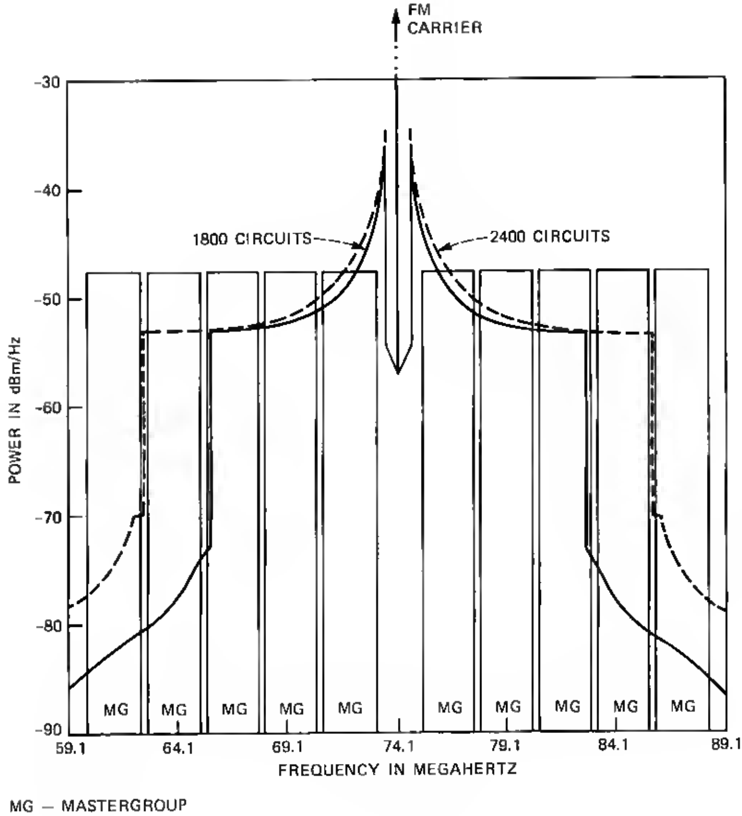

Fig. 5—AR6A and TH spectra.

4.2.2 Method of stabilization

As a result of choosing the IF center frequency of 74.12965 MHz, all the microwave generator frequencies and the shift oscillator frequency are multiples of 14.825930 MHz. Because the best crystal frequency stability is obtained around 5 MHz, the AR6A synchronization supply oscillator was chosen to have a frequency of 4.94197666 MHz, which is one-third of 14.825930 MHz. This oscillator is oven controlled and has a stability of two parts in 10^8 over the required temperature range and an aging rate of less than five parts in 10^{10} per day. In order to get all the harmonics needed for locking the microwave generators and for circuit convenience, the AR6A synchronization oscillator frequency is divided by 16 to obtain 0.30887354 MHz. This latter frequency is distributed to the phase-locked loops associated with microwave generators and the shift oscillators. The phase-locked loops contain circuitry that will hold the frequency at its last value

and prevent a frequency jump if the synchronization signal is lost. The AR6A synchronization oscillator supplies the synchronization for all 16 bays of a fully equipped repeater station and is protected by automatic switching to a second unit.

4.3 Signal recovery

The customer-to-customer frequency offset objective of the Bell System is ±2 Hz. This means that carriers used in translating baseband signals up and down in frequency must be very accurate in frequency. This is accomplished by locking tbese carriers to a primary frequency supply (PFS) which itself is locked to the Bell System master oscillator in Hillsboro, Missouri. Frequency-division multiplex systems such as LMX, MMX, and JMX all operate in this manner. A newly developed OMFS is provided in AR6A terminal stations to meet the frequency offset objective.

In the AR6A System no carrier is transmitted along with the AM sidebands, so one must be accurately generated in the receiving MMGT-R. The IF signal into the receiving MMGT-R can be a few hundred hertz from nominal because of accumulated frequency errors from intermediate repeaters. The receiving carrier generated in the MMGT-R receiver is controlled in frequency to compensate for the accumulated frequency errors by using recovery pilots (one in each half of the IF spectrum). These recovery pilots at the input to the receiving MMGT-R have the same accumulated frequency offset as the rest of the IF signal. The receiving MMGT-R translates each half of the IF spectrum down to the MMG spectrum independently. In each case, the received recovery pilot is selected from the MMG spectrum and is compared in a phase-locked loop with an oscillator locked to the local OMFS. The output error signal from the comparator is used to adjust the frequency of the carrier used in the receiving demodulator. In this way, the receiving carrier "tracks" the frequency offset of the incoming signal and the MMG signal is recovered with no frequency offset.

4.4 Equalization

4.4.1 Static

The objective for amplitude deviation from flatness over the 30-MHz channel for each switch section is ±0.5 dB. To help achieve this objective on a radio hop, each TR bay receiver includes a basic bay equalizer, which compensates for known systematic amplitude misalignments of the microwave and IF components. Mop-up equalizers are available in ±0.5 dB slope and parabolic shapes to enable each switch section to meet its ±0.5 dB objective. The amount of mop-up equalization required is specified automatically from switch section

amplitude response measurements made by the TSS-R System. Places are available in the 500A protection switch and in each radio receiver to mount the needed mop-up equalizers.

4.4.2 Dynamic

The objective for time-variant amplitude variations is that they be less than ±2 dB for 99.9 percent of the time. The primary source of transient amplitude variations is selective fading of the microwave signal due to unusual atmospheric conditions. An extensive measurement and analysis program was started in 1970 to determine the effects of selective fading on a 6-GHz microwave radio channel.[5] As a result of computer simulation studies made with the collected fading data, the following three strategies were recommended to minimize selective fading effects:[6]

1. Use space-diversity reception for each hop that has significant selective fading.
2. Use a simple automatic gain control (AGC) amplifier in each receiver.
3. Use a dynamic equalizer that will provide slope and parabolic shape correction at the end of each switch section.

The use of space diversity is recommended to reduce the amount of time the microwave signal is in a deep fade where the largest amplitude variations occur. This is discussed further in Section 4.7. The use of an AGC amplifier in each receiver to compensate for the flat gain portion of microwave signal variations is standard in radio systems. In the AR6A System, the AGC amplifier gain is controlled by the voltage average of the three received radio pilots. To compensate for the shape portion of the amplitude variations, a dynamic equalizer has been designed[7] and is used in each main station receiver. The dynamic equalizer contains one bump network located at each end of the IF band. The gains of these networks are continuously controlled by the voltage difference between the edge radio pilots and the center radio pilot of the received channel. Figure 6 shows a typical fade shape across the IF band before and after equalization.

4.5 Interference

4.5.1 Impairments

An important aspect of any new radio system design is the consideration of the interference environment. The AR6A System has to coexist with the existing FM radio systems, other AR6A routes, and self-interference. One effect of interference is to add to the background noise of the channel; this is compensated for by the inclusion of 32.3 dBrnc0 for interference in the system noise allocation.

Other effects are crosstalk, babble, and tone interference, which can

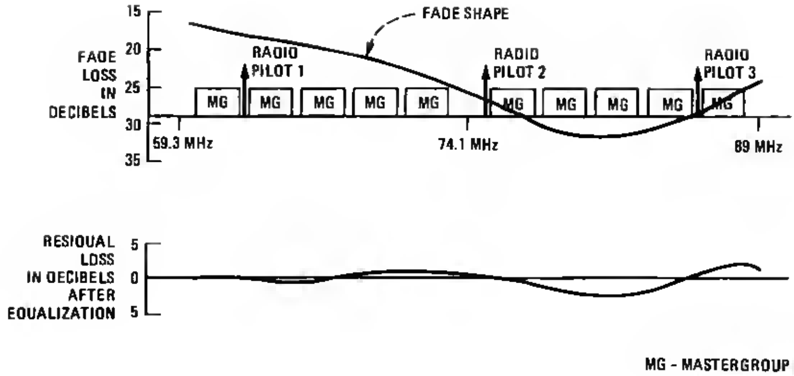

Fig. 6—Dynamic equalization of a fade.

occur when two AR6A channels carrying different traffic interfere with each other.

If both the interfering signal and the desired signal are voice signals and are exactly aligned in frequency, the effect is crosstalk. If the two signals are increasingly offset in frequency, the interference becomes less intelligible until, at ±500 Hz, the interference is judged to be unintelligible crosstalk and referred to as babble. Should the interfering signal be an idle circuit tone or a data signal, the effect will be tone interference regardless of any frequency offset. This type of coupling between two AR6A channels can occur at junction stations or between two routes not sharing a station but in the same geographical area. These effects must be evaluated in terms of tbe crosstalk, babble, and tone interference objectives. In FM systems, tbe poorer RF frequency stability and the effects of carrier spreading render these impairments negligible.

Another interference effect is talker echo that results from coupling—primarily antenna coupling—between the east- and westbound channels of the same route. For administrative purposes, the east- and westbound halves of the 4-kHz voice circuits are in corresponding locations in their respective channels. Tbus, if these two channels are within 500 Hz of each other, the result is talker echo. Beyond 500 Hz, the effect will be a babbled talker echo, which is judged to be almost as annoying. The magnitude of the talker echo may be described in terms of the effective return loss of the system.

4.5.2 Cochannel interference

To avoid interference from cochannel FM carriers, the center of the AR6A channel is left vacant. The noise effect of the FM sidebands is controlled by properly selecting the cbannel center gap and frogging

Table I—Impairment calculation summary

Impairment	Objective	Estimated Performance (Percent)
Crosstalk	≤ 1 percent	0.12
Babble/Noise	≥ -10 dB no more than 1 percent of time	0.32
Tone/Noise	≥ -10 dB no more than 1 percent of time	0.55

the mastergroups. The noise effect of another cochannel AR6A System is controlled by requiring at least a 64-dB signal-to-interference ratio.

Studies were conducted to evaluate the ability of the AR6A System to meet the crosstalk, babble, and tone objectives. These impairments are largely controlled by the antenna system discrimination against interfering signals and route layout. Most of AR6A installation would be on existing routes, which means antennas and routes are already fixed. A design choice that was open was the frequency stability of the radio line. As noted in Section 4.2, the microwave carrier supplies required stabilization to keep the radio pilots within the passband of their pick-off filters. Several stabilization plans witb different degrees of stabilization were analyzed to determine their effect on crosstalk, babble, and tone interference. These included a plan that introduced a series of fixed frequency offsets on different radio channels to reduce crosstalk. The results showed that a highly stabilized plan was the best for balancing the impairments. A summary of these impairments for the 4000-mile system model is shown in Table I.

One remaining cochannel interference that required analysis was the same route interference that gives rise to talker echo. The requirement for a 4000-mile system is an effective return loss of at least 30 dB. Calculations estimate that the return loss of the radio line is 41 dB.

4.5.3 Adjacent-channel and tertiary inference

The AR6A System has no significant signal-related energy outside of its channel bandwidth. Thus, adjacent-channel noise effects are negligible for adjacent AR6A channels. However, mutual problems occur when an AR6A and an FM channel are adjacent. If the FM channel is an RF squelch-equipped TH-3 System, this feature must be removed because the initiator noise slot is located inside the AR6A channel in a mastergroup position. Without removal the initiator would be continuously operated. Another problem is generated due to the wide bandpass of the IF filters needed in the FM systems to reduce their own channel noise. These filters couple into the FM receiver a portion of the adjacent AR6A signal, which is limited primarily by the cross-polarization discrimination of the antenna system. The noise

caused by this interference restricts the number of exposures to 10 or 15. In addition, the tertiary interference effect of a portion of the AR6A signal coupled into the adjacent FM channel is also undesirable. This AR6A signal when coupled back into the AR6A channel will produce modulation on the edge radio pilot and an amplitude shape deviation, depending upon the phase relationship between the signal and the interference. Estimates of these effects indicate they should be avoided if possible, but if they cannot be avoided during route conversion from FM to AR6A, then the AR6A channel adjacent to an FM channel must be either the protection channel or a working channel with the five adjacent mastergroups vacant.

4.6 Linearity

4.6.1 General

Low intermodulation distortion (IM) properly optimized relative to other noise contributors is a basic consideration in the design of a transmission system. It is of particular interest in the AR6A System since the achievement of satisfactory linearity in the transmitting microwave amplifier is a key factor in making the SSBAM Microwave System possible. Transmitting amplifiers with power-handling capacities comparable to those commonly used on current FM systems fall short of meeting SSBAM linearity requirements by some 20 to 30 dB. Achieving stable distortion reductions of this magnitude was thus a crucial design task. Furthermore, although transmitter nonlinearity is dominant, care must be exercised in the design of all other in-line elements to ensure that their cumulative distortion contribution is not excessive.

Since at microwave frequencies and even at intermediate frequencies we are dealing with narrowband channels, the only significant distortion contributors are the odd-order, nonlinear terms. In AR6A, third-order distortion is dominant, fifth order is on the fringes of importance, while seventh and higher odd-order terms are negligible.

A related and crucial design consideration is the question of how the distortions from tandem nonlinear networks combine within and between repeaters. This is referred to as tbe Law-Of-Addition (LOA) question. Differences between the extreme assumptions of coherent and noncoherent addition strongly influence a variety of design choices. For example, the LOA influences the optimum system drive level, it affects how frequently mastergroups must be relocated or frequency frogged, and it affects equalization strategies. For these reasons, studies and estimates of the LOA received early attention, while subsequent verification of the assumptions was an important element in the field evaluation.

4.6.2 *Distortion estimates*

To make system distortion estimates, first the distortion contribution must be estimated from individual system elements. This, in turn, must be based on some suitable measured parameter(s) indicative of the unit's nonlinearity. For AR6A computations, a practical approach starts from a power series description of the unit's input/output relationship. Functional ratios of the power series coefficients can then be related to measurable modulation coefficients and vice versa.

To estimate distortion, the broadband message load can be simulated by zero-mean Gaussian noise with appropriate spectral shaping. Multiple convolutions weighted according to power series coefficients may then be used to determine expected IM distortion. In AR6A, since the signal spectrum is flat, the IM noise computation can be greatly simplified by using the work of Y. L. Kuo.[8] Distortion-to-signal ratios are evaluated in terms of power series coefficients, which are then related to measurable modulation coefficients. The final result is expressed in the following relationships, which assume that the odd-order power series has no significant terms beyond the fifth

$$N_3 = 4.23 + 2P_{\text{out}} + M_{\alpha+\beta-\gamma}$$

$$N_{35} = 4.77 + 3P_{\text{out}} + \frac{1}{2}\left(M_{\alpha+\beta-\gamma} + M_{2\alpha-2\beta+\gamma}\right)$$

$$N_5 = 8.32 + 4P_{\text{out}} + M_{2\alpha-2\beta+\gamma}, \tag{1}$$

where

N_3 = ratio of third-order distortion power in a narrowband ΔW to signal power in the same bandwidth. The ratio is expressed in decibels and the band ΔW is located at the center of the simulated, spectrally flat, message load,

N_5 = the corresponding fifth-order power ratio,

N_{35} = the corresponding fourth-order power ratio being an interaction term between the third- and fifth-order distortion mechanisms,

$M_{\alpha+\beta-\gamma}$ = a third-order modulation coefficient expressed in decibels,

$M_{2\alpha-2\beta+\gamma}$ = a fifth-order modulation coefficient expressed in decibels, and

P_{out} = total simulated message-load power in dBm at the device output.

The noise-to-signal power ratios can be converted to dBrnc0s as follows:

$$noise\ (\text{dBrnc0}) = N + P_1 + 86.8, \tag{2}$$

where N is the noise-to-signal power ratio in dB and P_1 is the average signal power per 4-kHz message circuit at 0 transmission level (TL). These relationships involve a number of simplifying assumptions and should be used with caution. For example, tbe M values are assumed to be constants independent of drive level and frequency; addition of $M_{\alpha+\beta-\gamma}$ and $M_{2\alpha-2\beta+\gamma}$ in the expression for N_{35} is subject to some uncertainty because of the absence of product phase information in the definition of M; and, finally, the expressions apply at the band center of an idealized simulation of tbe message load. In AR6A applications, cross-checks have been made against pseudorandom noise load measurements[9] witb satisfactory agreement if nominal drive levels are not exceeded by more than a few decibels.

With typical values for an output traveling-wave-tube amplifier of $M_{\alpha+\beta-\gamma} = -90$ dB, $P_{out} = +25$ dBm, and $P_1 = -19.6$ dBm0, tbe estimated IM noise is 23 dBrnc0 per repeater. Taking account of product addition laws, thermal noise contributions, etc., led to the earlier assertion tbat distortion reductions of at least 20 dB are needed to make the SSBAM System viable.

4.6.3 Law of addition

For a string of n identical nonlinear devices, the law of addition (K) for intermodulation noise (IM) is defined by

$$W_n = K \log n + W \text{ dBrnc0}, \tag{3}$$

where

$$W_n = \text{intermodulation noise of the string,}$$

$$W = \text{intermodulation noise of one device.}$$

Odd-order distortion from some elements of a repeater are going to add systematically corresponding to $K \approx 20$. Other sources of repeater IM are going to accumulate in a random fashion corresponding to $K \approx 10$. The overall law of addition is going to be somewhere between those extremes and will depend on the relative magnitude of the two types of contributors. Clearly, the net value of K is going to be an extremely important factor in estimating total system noise on a long route.

In the case of IM contributed by repeater elements subject to predistortion correction, the residual distortion can be expected to have a random phase orientation. However, some departures from randomness will be experienced if there are systematic degradations in predistorter improvement due to frequency response or aging effects.

Nonlinear elements not subject to predistorter compensation, sucb as IF amplifiers, will generate IM that adds systematically. Again,

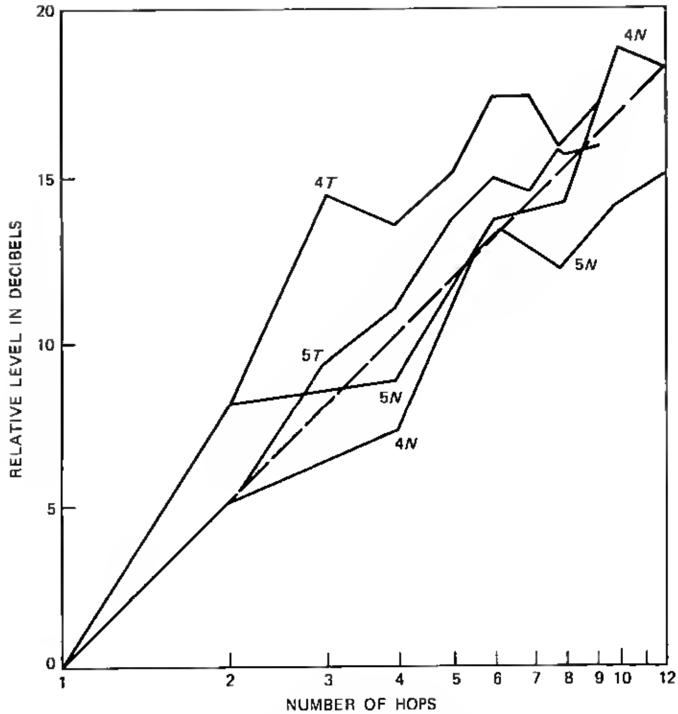

Fig. 7—Intermodulation noise law of addition.

however, there are modifying circumstances such as repeater delay distortion that in this case can reduce the rate of accumulation. Computations involving multiple convolutions of the signal indicate that on AR6A, delay distortion reduces the law of addition from 20 to approximately 19 near band center with larger reductions near the band edges.

For design purposes, law-of-addition estimates were based in broad terms on the power addition of transmitter IM, the voltage addition of receiver IM, and power addition of the combination. Depending on detailed assumptions, this led to estimates for K in the range 16 to 18.

Measurements using pseudorandom noise loading[9] for 12 pairs of repeaters in the initial field installation yielded an average value $K = 16.9$. These same repeaters were then connected in loops of 2 through 12 hops, and the pseudorandom noise load results for radio channels 4 and 5 ($4N$, $5N$) shown in Fig. 7 were obtained. The dotted line in the figure refers to the expected law of addition ($K = 16.9$). Measurements using a three-tone test ($4T$, $5T$) are also shown in the figure. Reasonable agreement with the expected law of addition is observed.

4.7 Application of frequency- and space-diversity protection

4.7.1 Microwave propagation of the AR6A signal

In the early development of AR6A, it was recognized that it would be necessary to characterize the effects of selective fading on the broadband SSBAM signal. Propagation studies were conducted in 1971 on a 26.4-mile path from Palmetto to Atlanta, Georgia. The studies quantified the fading effects on a statistical basis and determined many of the basic system design features, including the choice of the three radio pilots to control system gain, the type and amount of dynamic equalization, and the algorithms for space- and frequency-diversity switching.[10]

In microwave radio system design, multipath (Rayleigh) fading is usually characterized by the equation[11]

$$T(L) = rT_0L^2,\ L < 0.1, \tag{4}$$

where

L	=	the ratio of received carrier amplitude to nominal or free-space received carrier amplitude,
T_0	=	time base or total time of the study,
r	=	fade occurrence factor representing the fraction of time that selective fading occurs, and
$T(L)$	=	time in seconds during the period T_0 that the received carrier amplitude ratio is below the level L.

This relation is descriptive of any single frequency in the AR6A spectrum. The propagation studies expanded this signal characterization to four frequencies. Statistics representative of the fading of any independent frequency in the spectrum were generated with conditioning on the state of the three radio pilots. The equation modeling the fading becomes

$$T(L) = rT_0L^2(U(L) + P(L)), \tag{5}$$

where

$U(L)$	=	the conditional probability that the radio pilots are less faded than the ratio L given that the frequency of interest is faded at least to the ratio L, and
$P(L)$	=	$1 - U(L)$.

The probability $U(L)$, shown as the curve $L_F = L$ in Fig. 8, is less than 0.1 for fades less than about 36 dB ($L = 0.016$) and increases monotonically with fade depth to about 0.5 for fades greater than 48 dB ($L = 0.004$). Since the radio pilots are used to control the system gain and switching functions, this characterization allows various equalization and switching plans to be evaluated.

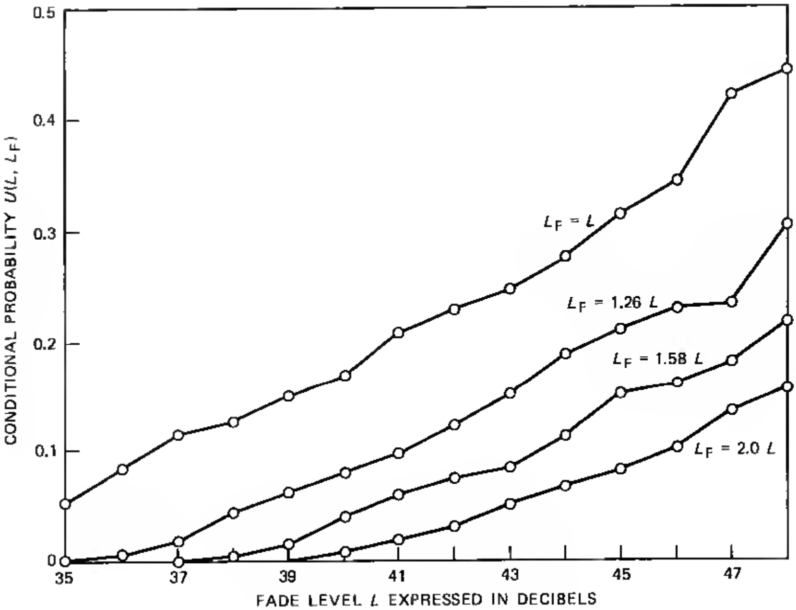

Fig. 8—The conditional probability $U(L, L_F)$.

In addition to the four frequency fading characterization, the 1971 propagation data were also used to characterize the amplitude response of the signal during fading. The data were used as the input to a computer program that simulated the response of the dynamic equalizer. The results of this study are shown in Fig. 9. This plot indicates the expected average severity of gain deviations during fading. The averaging process includes an average over all voice-circuit locations in the signal spectrum. The plot is similar to a cumulative distribution with the maximum fade level of the radio pilots as the independent variable. The 2-dB gain deviation limit corresponds to the dynamic equalization objective. As indicated in the figure, fades with radio pilot attenuation less than 30 dB contribute essentially no gain deviation time. For fades with radio pilot attenuation exceeding 40 dB, comparison of Fig. 9 with the Rayleigh model of eq. (4) shows that almost all of the fade time has gain deviations exceeding ±2 dB. These results led to the recognition that in order to meet the system 2-dB gain deviation objective, space-diversity switching at radio pilot fade levels in the range of 30 to 40 dB would be required.

4.7.2 Frequency- and space-diversity switching during multipath fading

With the recognition that both frequency- and space-diversity switching would be required for AR6A, a fading model including the

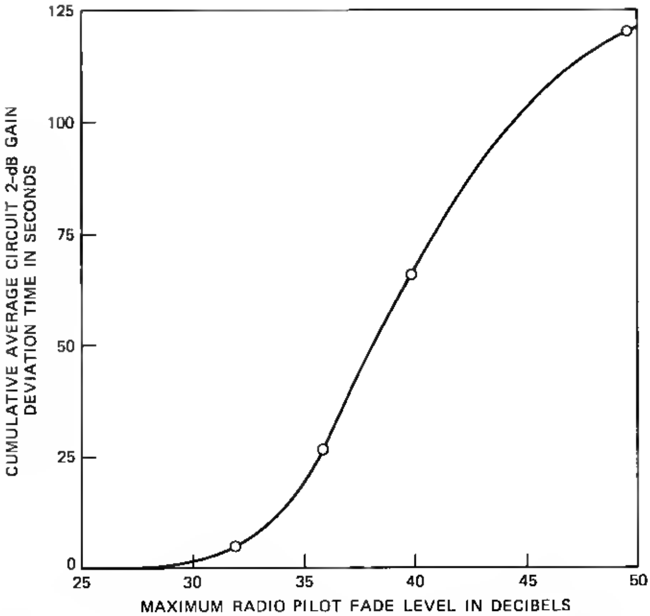

Fig. 9—Average gain deviation time of an AR6A circuit for 600 seconds of multipath fading at the 30-dB level.

effects of both switching systems was developed.[6] The resulting equation representing the fading performance of a hop equipped with both types of switching is

$$T_p(L) = \frac{rT_0L^2}{I_s(L_s)}\left[U(L, L_F) + \frac{P(L, L_F)}{I_F(L_F)}\right], \quad L \leqslant L_F < L_S < 0.1, \qquad (6)$$

where

L_F = the pilot fade level corresponding to the frequency-diversity switch threshold,

L_S = the pilot fade level corresponding to the space-diversity switch threshold,

$I_F(L_F)$ = the improvement factor resulting from frequency-diversity switching, typically $I_F > 1$,

$I_S(L_S)$ = the improvement factor resulting from space-diversity switching, typically $I_S \gg 1$,

$U(L, L_F)$ = the conditional probability that the three radio pilots are less faded than L_F given that the frequency of interest is faded to level L,

$P(L, L_F)$ = $1 - U(L, L_F)$, and

$T_p(L)$ = time that the protected signal is faded below level L.

The quantities I_F and I_S vary as L^2 but differ from the conventional,[10] single-frequency improvement factors. Typical values in tbe current system design are $I_F = 15$ and $I_S = 100$. The conditional probability function $U(L, L_F)$ is shown in Fig. 8 witb tbe relationship between L and L_F as a parameter. The results in the figure are calculated from the 1971 data without smoothing. Since $I_F(L_F) > 1$, eq. (6) sbows that higher values of $P(L, L_F)$ are desirable. The increase in $P(L, L_F)$ corresponds to an increase in the fade time that is protected by frequency-diversity switching and a decrease in outage time.

The 2-dB gain deviation time for a path protected by frequency- and space-diversity switching is modeled by the equation[6]

$$T_2(L) = \frac{rT_0}{0.6}\left[D(L_s) + \frac{D(L_F) - D(L_s)}{I_s(L_s)} + \frac{D(L) - D(L_F)}{I_s(L_s)I_F(L_F)}\right], \quad L < L_F < L_s, \tag{7}$$

where the function D is the 2-dB gain deviation time given in Fig. 9. Equations (6) and (7) formed the basis for evaluating various space- and frequency-diversity switching algorithms.

4.7.3 Reliability and dynamic equalization requirements

During the development process, the performance of the radio system with respect to the reliability and dynamic equalization objectives was evaluated for several space- and frequency-diversity switching algorithms. In particular, various combinations of the switching levels L_S and L_F were studied. System performance for both voice and voiceband data was included. It was found that lower values of L_S and L_F improved the reliability performance but degraded the dynamic equalization. The current system design represents an approximate optimum in the trade-off between these requirements.

The space-diversity switching level was chosen to correspond to a 36-dB fade on a 27.1-mile path. For longer or shorter paths, the switching level varies inversely with the received signal level. The frequency-diversity switching level was chosen to be 53 dBrnc0 corresponding to a 44-dB fade on a 27.1-mile path. With this switching arrangement, approximately one-half of the hops in an average fading area are expected to require space diversity.

4.7.4 Computerized implementation

An interactive computer program was developed to facilitate the application of frequency- and space-diversity protection to new AR6A switch sections.[6] The evaluation of a proposed section's performance with respect to the outage and dynamic equalization objectives is

accomplished by the program after input data are supplied by the program user. The data are used to characterize the expected fading on the various hops in the section. For each hop, the input data include a climatic factor; the mean annual temperature; the hop length, roughness, and fade margin; and a description of any proposed space-diversity antenna.[10] The program first evaluates the performance of the section without space diversity. The estimated performance is compared to the objectives after prorating them to the length in miles of the section. If the objectives are met, the program stops and the route can be installed without space diversity. If they are not met, the program reevaluates the performance with space diversity applied initially on the worst fading hop. The program continues in this manner until the objectives are met. The route would then be installed with space diversity on the specified hops.

4.8 Mastergroup frogging

Noise, reliability, and dynamic equalization in AR6A are functions of voice-circuit location in the IF passband. Circuits located near the IF band center receive relatively high levels of interference noise from FM-FDM and FM-TV systems. Reliability and dynamic equalization are best for circuits located near one of the radio pilots. Because of these variations, more uniform performance is attained on long trunks by varying their location within the IF spectrum. The variation is accomplished by interchanging or frogging mastergroups at specified distances. The maximum allowable frogging distance chosen for field applications is 800 miles. This value provides acceptable system performance and reduces the amount of multiplex equipment required solely for frogging. The effects of frogging distance on system performance are described in the following sections.

4.8.1 Noise performance

The system noise components that are influenced by frogging include: intermodulation noise, radio pilot modulation noise, and worst-circuit FM RF interference noise. The levels of these components all increase with frogging distance and are listed in Table II for distances of 400, 800, and 1600 miles. The intermodulation noise increase with

Table II—Noise performance with various frogging rules

Noise Type	Noise in dBrnc0 400-Mile Rule	800-Mile Rule	1600-Mile Rule
Intermodulation	31.7	33.3	34.0
Radio pilot modulation	16.1	21.1	26.1
Worst-circuit FM RF interference	27.4	30.4	31.9

frogging distance is due to the radio receiver. The receiver intermodulation products produced on hops within a frogging section are nearly coherent. A small reduction, estimated to be 2.6 dB for an 800-mile frogging section, results from the phase characteristic of the IF filter. The receivers' products in different frogging sections are incoherent because of the changed signal. The radio pilot modulation noise also increases with frogging distance as a result of hop-to-hop coherence.

Although the average noise resulting from the FM RF intereference does not change with frogging distance, the distrihution of the noise does. Circuits located near the center radio pilot experience maximum interference. When the frogging distance is increased heyond 400 miles, some circuits receive significantly more noise than the average. The resulting worst-circuit noise is shown in Table II.

4.8.2 Reliability and dynamic equalization performance

Since the noise initiator slots for the 500A Protection Switching System are located near the radio pilots, voice circuits located near the pilots receive relatively good selective fading protection. For these circuits unprotected fade time is small. For circuits located hetween the radio pilots, some selective fades can cause outage without producing enough noise in the slots to initiate a switch. As a result, the outage performance of the system varies with IF frequency. With a 400-mile frogging rule, all mastergroups transmitted 4000 miles occupy each mastergroup location in the signal spectrum for approximately 400 miles. When the frogging distance is extended heyond this interval, the performance is no longer uniform. With the 800-mile rule, calculations indicate that the outage of the worst circuits will exceed the average circuit by 44 percent. To ensure that these circuits meet the overall multipath fading objective, an algorithm was added to the computer program for the application of space diversity. For switch sections located in frogging sections between 400 and 800 miles in length, worst-circuit performance is calculated and compared to the ohjective. Additional space-diversity protection is then required for the switch section to meet the system requirement. This procedure allows the engineers responsihle for a route to trade off the cost of additional multiplex required for a shorter frogging section with the cost of additional space diversity required for a longer one.

For frogging distances greater than 400 miles, the dynamic equalization performance of the system parallels the reliahility performance. Worst-circuit gain deviation time with the 800-mile frogging rule is approximately 48 percent greater than the average circuit time. This factor is also included in the computer program for the application of space diversity, and the worst circuits are required to meet the system ohjective.

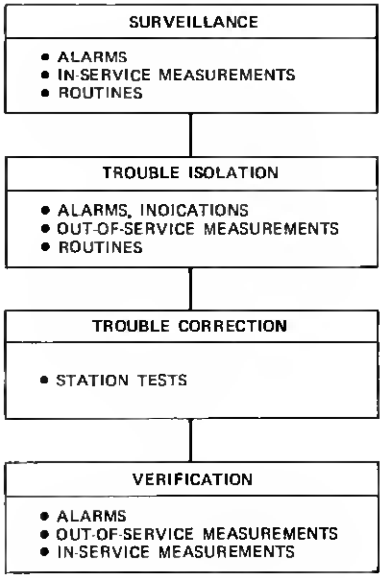

Fig. 10—AR6A generalized maintenance plan.

4.9 Maintenance

4.9.1 General

Maintenance was discussed in general terms in Section 1.6 with particular mention of the importance of adequate transmission surveillance capability. In AR6A, the new surveillance functions are combined with traditional remote alarm and reporting features to form an overall maintenance plan that is summarized in very general terms in Fig. 10.

The alarm reporting system is a full-time monitoring facility using either C1 or E-type alarm remotes under the centralized jurisdiction of a SCOTS or TASC central minicomputer. In general, remote alarm reporting is limited to isolating trouble to a particular station and direction of transmission, not the particular unit in trouble. Locally, however, more detailed visual indications and test points simplify the trouble isolation process. This approach is based on the premise that prior knowledge of the detailed trouble condition is unnecessary if it is assumed that, on a station visit, the technician is equipped to deal with any on-site problem or any additional problems that become known enroute.

Except for a few legally required routine tests, maintenance is performed on an as-needed basis. When a trouble bas been identified and isolated, a technician is dispatched to the trouble site with a defined set of spare parts and station test equipment. The principal station test sets are:

1. Transmitter-receiver transmission test set
2. Scanning intermodulation test set
3. Portable rubidium frequency standard
4. Pilot selection test set
5. TWT power supply test load.

4.9.2 Transmission Surveillance System

The AR6A Transmission Surveillance System—Radio (TSS-R) consists of programmable equipment for access and testing located at radio switching stations. It can perform a variety of transmission measurements under the direction of a central minicomputer. Communication between the central computer and remote measuring sites is via *DATAPHONE** data communications service with its attendant flexibility and expandability. Unlike the alarm reporting system, TSS-R measures system performance on a scheduled or as-needed basis, providing snapshot rather than continuous information.

Figure 11 is a block diagram of TSS-R. The central minicomputer has a peripheral disk storage capacity of approximately 20 Mb allocated to program, database, and data storage functions. Automatic call-out units provide DDD access to the measuring remotes as well as to maintenance and other centers programmed to receive reports. It is expected that five central computers will be capable of covering all AR6A deployment within the continental United States.

At switching stations, test access, measuring equipment, and data interchange with the central computer are under the control of a microprocessor with its associated firmware. Physically, these functions are grouped in the TSS-R distribution bay as indicated in Fig. 11. All measurements are performed by a Selective Transmission Measuring Set (STMS) with a frequency range of 10 kHz to 160 MHz. The set is controlled by the distribution bay microprocessor via an IEEE control bus. Programmable functions include level and frequency measurements, bandwidth selection, and the selection of a phase-jitter measuring mode.

Switched access for measurement purposes is provided at transmitting and receiving mastergroup combiners and at transmitting and receiving 500A switches. Measurements at mastergroup combiners can be made on a bridged, in-service basis only; measurements at the 500A switches can be made either on an in-service or out-of-service basis.

In-service measurements can be made conventionally using bridging hybrid transformers in conjunction with director switches to route the selected test point to the STMS. Signals available for measurements

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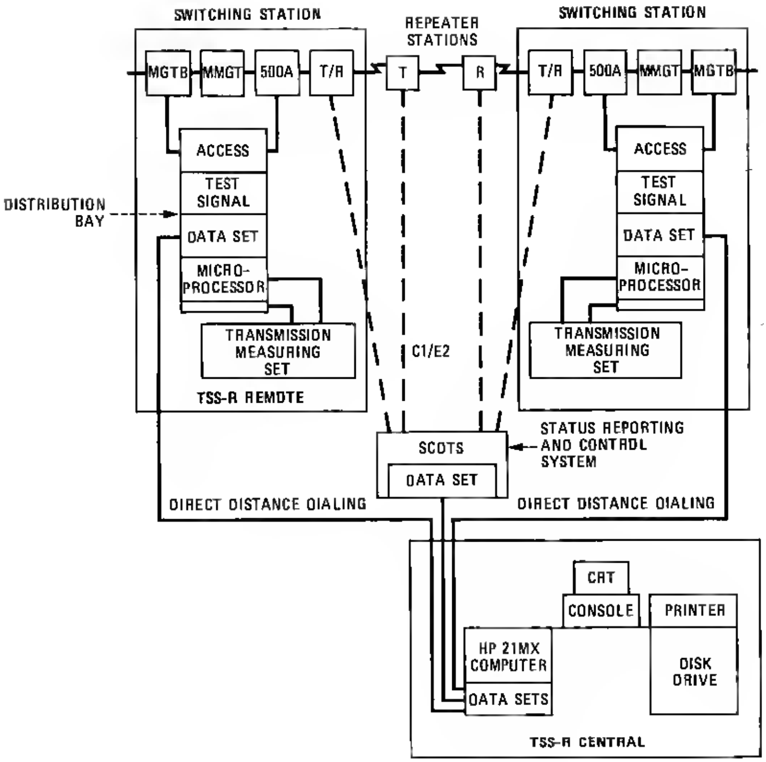


Fig. 11—Transmission Surveillance System.

are elements of the normal system load such as mastergroup pilots, system pilots, and intermastergroup noise. Since in-service measurements are made without affecting the main transmission path, they are made frequently and routinely at intervals of approximately one week.

On the other hand, out-of-service measurements require that service be temporarily transferred to the protection channel. This frees the selected working channel for end-to-end switch section measurements. To measure the channel, access at the head end of the switch section is provided by the 500A maintenance switch as indicated in Fig. 12. Since operation of a maintenance switch opens the channel and removes normal pilots, a substitute set of pilots must be supplied via the maintenance measuring path (see Fig. 12). At the receiving end of the switch section, the channel under test is routed to the STMS for making the selected out-of-service measurements.

Since the operation of a maintenance switch can be done under program control, safeguards must be provided against untimely oper-

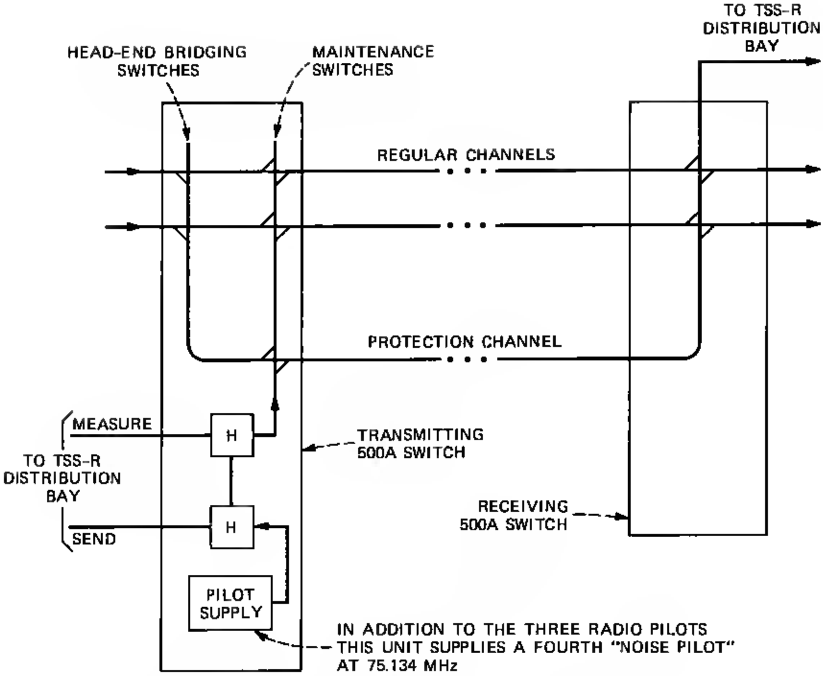


Fig. 12—Simplified diagram of switch section out-of-service test access arrangements.

ation of the switch by TSS-R. This is achieved by making the 500A control circuits the ultimate arbiter of all switching decisions.

Some out-of-service measurements require only that the head-end of the channel under test be terminated. Otber tests require the insertion and measurement of a test signal at the head end of the channel as well as its measurement at the receive end. Provisions for inserting test signals, combining them with pilots, and providing head-end measuring access are shown in Fig. 12. For example, to measure out-of-service amplitude response, a comb signal with a tone spacing of 130 kHz that encompasses the entire IF band is available from the distribution bay. This signal, when needed, is sent to the test signal input port (Fig. 12) and measured at each end of the channel under test. The measured data are returned to the TSS-R central minicomputer where a comparison of transmitting and receiving levels provides the desired amplitude response characteristic for tbe channel.

Special mention is made of the following out-of-service switch-section measuring capabilities:

1. Spurious modulation—This involves the insertion of a +5 dBm0 test tone (83.168 MHz) at the head end of the switch section. At the receiving end, TSS-R looks for spurious modulation sidebands on the

test tone. These might be due to modulation of the test tone by spurious switching tones from a bad power supply, spurious modulation by a faulty microwave local oscillator, or spurious modulation by some other unwanted mechanism.

2. Linearity—This measurement is of special interest for verifying continued satisfactory adjustment of transmitter predistorters. Two high-level (+17 dBm0) test tones located ±44 kHz on either side of the 74.13-MHz channel center frequency are inserted at the head end of the switch section. Third-order nonlinearities produce IM products located 88 kHz on either side of the radio-line pilots. These products are measured at the receiving end of the switch section as an indication of switch section linearity. Positioning the +17 dBm0 full-load test tones close to band center minimizes the impact of cochannel interference on other systems. In other words, the tones are no worse from an interference standpoint tban cochannel FM carriers.

3. Transmitter gain check—Tbe +17 dBm0 test tones mentioned in (2) can also be used as a coarse check on transmitter gain. When turned on at the head end of a switch section, power monitors on tbe output of each succeeding transmitter provide a remote indication if the power is within a ±3 dB window of nominal.

A complete listing of all in-service and out-of-service tests is given below.

1. In-service tests—switch section
    (a) Pilots—level and frequency
    (b) Intermastergroup noise
    (c) Pilot slot noise—before pilot insertion
2. Out-of-service tests—switch section and hop by hop
    (a) Idle noise
    (b) Noise and tone scan
    (c) Linearity
    (d) Amplitude response
    (e) Interference
    (f) Cross-polarization discrimination
    (g) Transmitter gain
    (h) Space-diversity switch point
3. Other tests
    (a) Head-end pilot supply on 500A
    (b) Phase jitter—in-service and out-of-service
    (c) Diagnostic tests

4.9.3 Stress-test and trouble-isolation features

Distinct from, but enhanced by, TSS-R are a number of supplementary features for stress testing and trouble isolation. Central to implementing these features is the capability to remotely operate any

selected resupply switch at intermediate repeaters via the alarm reporting and command system. When a resupply switch is operated, a locally generated set of pilots is inserted into the channel under test. By measuring the channel with TSS-R at the receiving end of the switch section, it is possible to characterize systematically shortened portions of the switch section to isolate trouble.

To ensure that a resupply switch can only be operated remotely on an out-of-service channel, the switch command is enabled by the presence of the noise pilot on the out-of-service channel (see Fig. 12). Since the noise pilot can only be present subsequent to the operation of a head-end maintenance switch and the prior transfer of service to a protection channel, the requisite protection is provided.

An important additional function of the noise pilot is associated with the switching system preemption feature. If TSS-R is measuring a foreshortened portion of a channel in a switch section, rapid restoral of the intermediate resupply switch is essential if the channel under test has to be preempted for service. Since a first step in the preemption process is to pull down the head-end maintenance switch and thereby remove the noise pilot provided by the head-end resupply, all downstream resupply switches are automatically disabled and returned to normal. This avoids the slow restoral procedure that would result if resupply switches had to be reset via the alarm reporting and command system.

Trouble isolation capabilities associated with the remote control of resupply switches are further enhanced by providing means to remotely modify the resupply signal. For example, the two high-level test tones used for switch section linearity measurements can also be turned on at intermediate resupply points. This provides the capability to isolate hops with high nonlinearity by looking at systematically foreshortened portions of the switch section. The isolation of linearity problems to a particular hop is further enhanced by turning on the aforementioned linearity test signal at a selected intermediate station; but instead of applying the radio pilots at their normal −10 dBm0 level, they are applied at 0 dBm0. This enhances the third-order nonlinearity product contributed by the first hop of the foreshortened switch section by 10 dB. At succeeding receivers on the switch section, AGC restores the radio pilots to −10 dBm0 and correspondingly reduces the high-level test tones by 10 dB to +7 dBm0. Thus, the third-order products contributed by succeeding hops are reduced by 20 dB, thereby making the first hop contribution dominant.

Another stress test feature is provided by remotely commanding the resupply pilots to be inserted 32 dB below their normal level of −10 dBm0. When this is done, AGC on the first receiver beyond the resupply point increases its gain by 32 dB to restore the pilots to their

normal −10 dBm0 level at the receiver output. Tbis enhances tbe front-end idle noise contribution of that particular receiver by a corresponding amount and will, therefore, be dominant when TSS-R measures noise at the end of the switch section. In effect, therefore, this measurement gives an indication of the receiver noise figure on the artificially faded hop. There is a corresponding 32-dB enhancement of incident interference on the faded hop providing a means for identifying the interference level and point of entry. This same technique may also be used to measure the level of the nearest radio pilot in the adjacent AR6A channel to obtain a measure of cross-polarization discrimination on a hop-by-hop basis.

V. TESTING

5.1 Laboratory testing

A test facility was established at Merrimack Valley to perform initial testing of AR6A bays. This test facility served the needs of developing shop and field testing information, initial testing for radio bay components, and pursuing problems observed in the later planned field trial program. Two sets of frequency-compatible bays were installed along with a support bay. The bays were configured so that each set had a main-station-configured bay and a repeater-station-configured bay. This arrangement allowed for the greatest flexibility for an ongoing testing program.

Figure 13 depicts the laboratory bay arrangement. Bays 1 and 2 were configured as main station bays. The waveguide runs connecting repeater bays 3 and 4 contain RF preamplifiers and the loss of eacb run was built out to simulate a nominal hop length of 27.1 miles (61.7 dB of section loss). Two MCSS supplies were available in the support

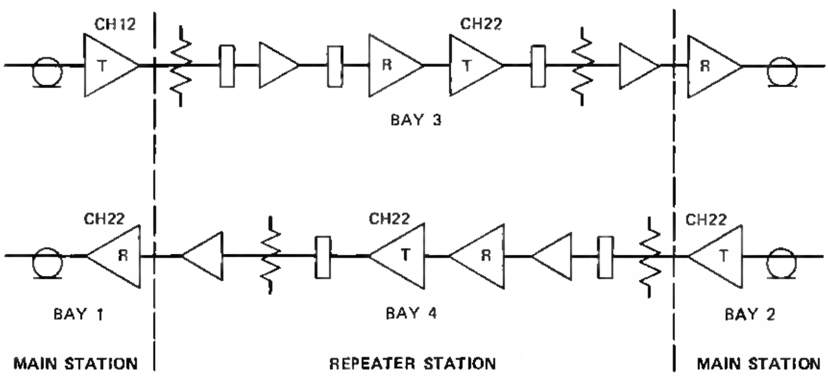


Fig. 13—Laboratory bay arrangement.

bay to allow for all bays to be locked to the same unit or for separate MCSS signals for bays 1 and 2 as testing required.

Initial testing concentrated on tests and measurements to ensure that an assembled bay met system requirements. Extensive tests were performed to isolate and reduce noise pickup and cross-coupling of signals in the bay wiring. These and results from the later field trial showed that a frame filter was necessary to filter the power from the −24 volt plant if noise objectives were to be met.

Modular design of the radio bay implied that a set of pretested modules could be inserted into a basic framework and a working bay obtained with a minimum of alignment. Initial testing was directed toward this goal. It was necessary to specify a series of tests for each module to ensure that when a set of modules was assembled into a bay, the bay performed satisfactorily. Test procedures for the overall bay were then developed for bay alignment. Once these procedures were deemed sufficient, they were incorporated into Bell System Practices (BSPs), which were then debugged using the laboratory bay facility.

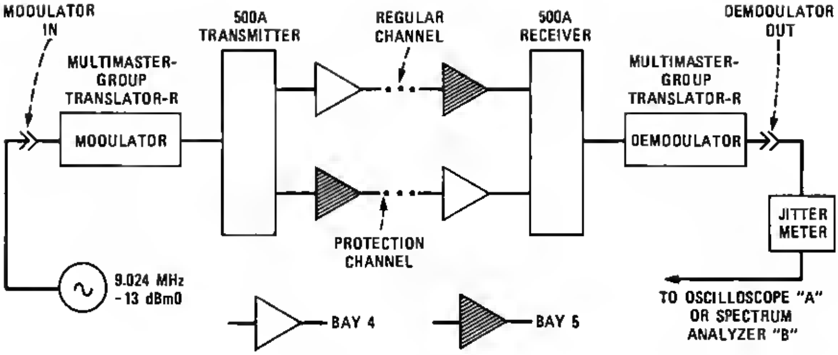
5.2 String tests

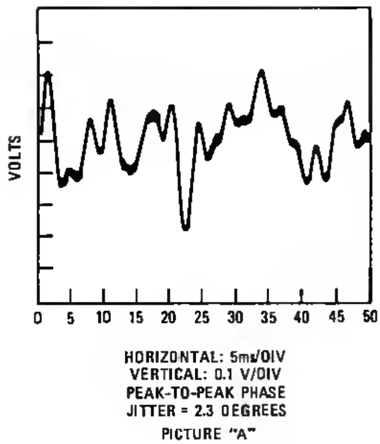
Since all components of the AR6A System were designed and available at Merrimack Valley, a tandem test arrangement was achieved by utilizing trunking between laboratories to construct a complete system comprised of MGTBs, MMGT-R multiplexing equipment, 500A Switching System, and the radio bays. This permitted injecting a signal into the system at basic mastergroup level and testing for switching transients with tandem units. A fade could be introduced producing a space-diversity switch, and as the fade was increased, correct switching activity for the 500A switch and the pilot resupply function in a radio bay could be observed and tested.

Noise load tests were performed on the tandem system, first on the MMGT-R connected back to back, then with the loopback at the 500A switch, and finally with a radio bay. This allowed testing of up to a four-hop switch section.

Phase jitter was also investigated on the system. Figure 14 depicts the test setup for a typical measurement. Pictures A and B in the figure show examples of the demodulated phase-jitter voltage display on an oscilloscope and a spectrum analyzer, respectively. Peak-to-peak switch-section jitter, measured in this fasbion, is typically 1.2 degrees.

This laboratory facility was used constantly over the next two years as the minitrial was conducted in western Massachusetts and the field trial was conducted in Missouri. Problems seen in the field were





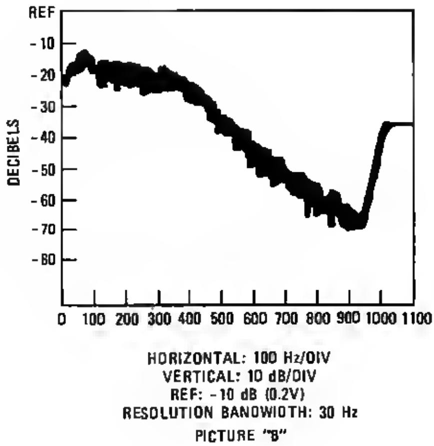


Fig. 14—Phase-jitter measurements.

pursued on the laboratory setup, thus eliminating a great deal of travel time and allowing testing, which led to a rapid resolution of problems.

For example, during the minitrial in western Massachusetts, a fade deep enough to produce either a space-diversity switch or pilot resupply switch caused multiple switching activity. The laboratory setup showed that although the average signal level was insufficient to call for the switch, switching was being initiated by noise spikes due to a peak detector with minimum filtering. Modifications were made to the detector circuitry such that switching was done on an average value over a few milliseconds rather than on an instantaneous peak value, thus eliminating the great number of switches that were occurring.

5.3 Ashburnham-Wendell field trial

5.3.1 Configuration

A field trial consisting of a one-hop loopback of AR6A prototype radio bays was conducted during the period of October 1977 to July 1978 between Northeastern Area Long Lines radio stations in Ashburnham and Wendell, Massachusetts. The Ashburnham station was equipped as a main station and the Wendell station as a repeater site. The hop length was 29.3 miles, and BTL model 656A microwave preamplifiers were used at both receivers. The Ashburnham radio bay transmitted on radio channel 22 (6226.89 MHz) witb vertical polarization and the Wendell bay transmitted on channel 12 (5974.85 MHz) with horizontal polarization, which made both bays standard in their channel arrangements. Both stations had prototype support bays that contained the pilot resupply and microwave carrier synchronization supply (MCSS) equipment. In addition to the radio equipment, each station was equipped with a PDP-8 computer which served as a Data Acquisition System (DAS) for complete monitoring and recording of all bay alarm and indication activity. A simplified diagram of the trial equipment is shown in Fig. 15.

5.3.2 Installation and alignment

As a test of the modular design concept Western Electric installers installed the basic bay framework and wiring. The actual assembly of the TR modules in the bay framework was performed by AT&T Long Lines personnel. The installation process was pbotographed and these photographs along with the documentation from Bell Laboratories were used to generate the installation Bell System Practices.

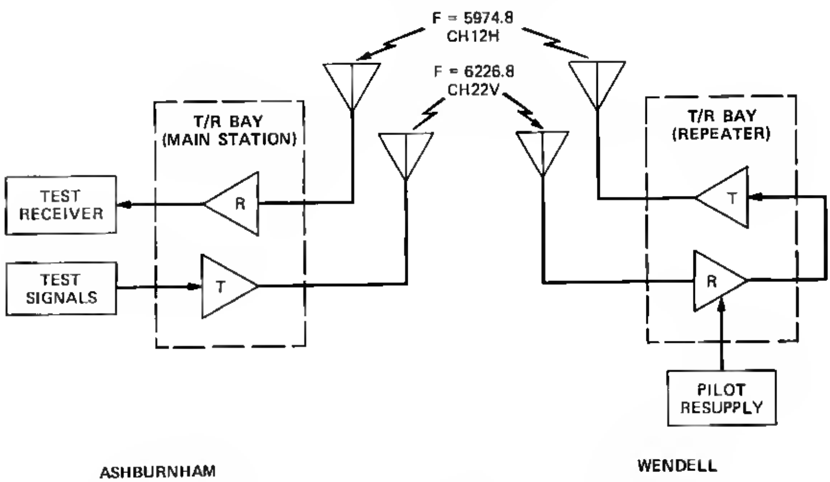


Fig. 15—Ashburnham-Wendell field triɐl equipment configuration.

5.3.3 System performance

Prior to shipping, the AR6A radio equipment underwent extensive laboratory measurements to fully characterize it. The measurements included thermal and intermodulation (IM) noise, and amplitude response. Initial system measurements made on the Ashburnham-Wendell installation showed good agreement with the laboratory results. Received signal levels agreed with calculated values indicating nominal section loss in the two directions of transmission. These results were further confirmed by thermal noise measurements. Long-term measurements were conducted on received signal strength, IM performance, and thermal noise. The results of these measurements indicated performance adequate or better than that required to meet system requirements. In particular, the long-term behavior of the IM noise was encouraging, indicating tbat the predistorter realignment intervals would be acceptably long. Examination of the received signal strength and noise slot data during fading activity indicated that the AGC amplifier and dynamic equalizer responded adequately and that space-diversity switch requests were generated at the planned level of 36 dB of fading.

5.4 Factory testing

Historically, radio bays have been installed and tested on site by Western Electric installers. Fully tested and operating bays are then turned over to the operating company. The AR6A modularity concept changed this procedure to one where the customer receives factory tested modules and assembles them to produce a working bay. To ensure that the customer could bring his equipment on line in a timely manner, two procedures were initiated. First, a level of spares was specified that should ensure inhand replacement units to offset initial failures and units damaged in shipment. Secondly, a factory testing program was initiated requiring that all modules be assembled in a test bay and functionally tested before sbipment. Both of these procedures are now standard practice.

5.4.1 Bay alignment

The set of modules comprising a radio bay are installed into test bays and then the bay is aligned. Any units not functioning correctly are replaced and trouble sheets on the failed units are filed. The data collected in this procedure are then used to identify problem units and the type of problem often helped identify the solution.

5.4.2 Back-to-back testing

To ensure that a quality product was sbipped from the factory, the eight performance tests listed below were performed on each aligned bay:

1. Amplitude response
2. Phase jitter—TR pair
3. Phase jitter—microwave generator
4. Spurious tones
5. Spurious modulation
6. Thermal noise
7. Intermodulation noise
8. Pilot resupply operation.

When factory production was first begun, the bays were produced in frequency-compatible pairs. After bay alignment was completed, the pair was connected back to back (at RF) and the performance tests conducted. As production increased, test bays containing a frequency shifter were constructed so that the performance test could be performed on individual bays. After 126 bays had been tested it was determined that other bay tests were sufficient, so that back-to-back tests were discontinued.

5.5 Missouri trial

During the period from July 1979 through June 1980, an initial evaluation of AR6A was conducted on a six-hop trial switch section between Hillsboro and Windsor, Missouri. This was part of a new 6-GHz route being established between Hillsboro, Missouri, and La Cygne, Kansas, for the first service route of AR6A (see Fig. 16). To allow field evaluation of upper and lower sideband transmitter modulators, radio channel 4 employing the lower sideband and channel 5 employing the upper sideband were installed. This arrangement also allowed for the measurement of adjacent-channel interference, an important factor in overall noise performance.

5.5.1 Installation

The 6-hop trial route was equipped as a two-way, 1 × 1 frequency-diversity protection system. Hillsboro and Windsor were equipped as terminal main stations and the five stations, Richwood, Rosati, Brinktown, Barnett, and Cole Camp were the connecting repeater stations. Installed at each of the repeater stations were four repeater bays and a support bay. Hillsboro, which is a terminal main station, was equipped with standard radio bays configured for main station application. In addition to the radio bays, a 500A protection switch, MMGT-R, 500B protection switch, and MGTB multiplex were also installed.

Windsor is a repeater station on the final expansion of the route to La Cygne, but for this trial was to serve as a terminal main station for AR6A. This required that two transmitter-only bays and two receiver-only bays (standard options) be installed at Windsor for normal

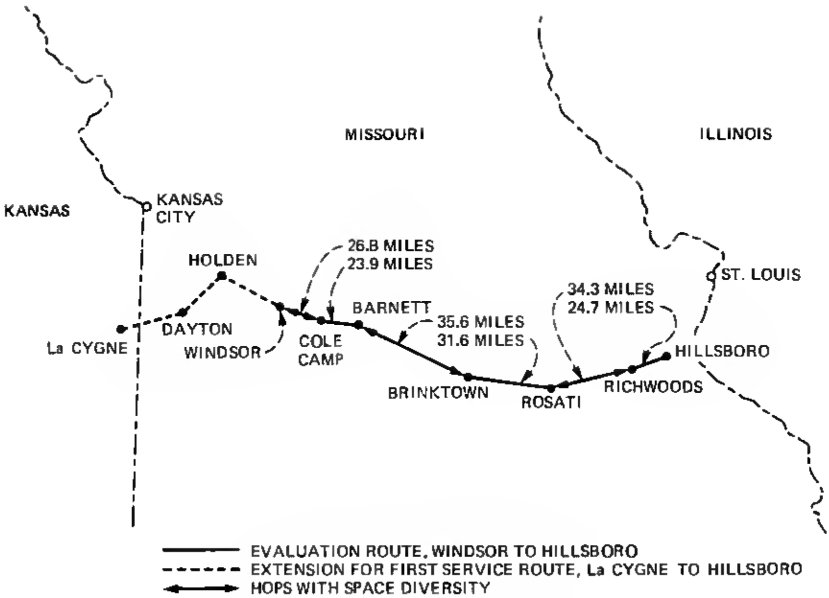


Fig. 16—First service route of the AR6A System.

connection to the indoor waveguide. And, of course, a 500A protection switch, MMGT-R, 500B protection switch, and MGTB multiplex were also installed. To allow signals transmitted from Hillsboro to be looped back to Hillsboro, a set of mastergroup connectors also were installed at Windsor.

Alternate hops on this route were equipped with the space-diversity option. This required that a space-diversity antenna be installed at all stations but Hillsboro.

A Bell Laboratories prototype TSS-R remote distribution bay was installed at both Hillsboro and Windsor. This allowed field evaluation of the distribution bays and their interaction with the TSS-R central minicomputers located at Bell Laboratories.

In addition to the radio equipment, each station was supplied with a PDP-8 computer that served as a Data Acquisition System for complete monitoring and recording of all bay alarm and indication activity. This system was connected to a PDP-8 computer at Bell Laboratories, Merrimack Valley, to allow for continual monitoring of the trial.

5.5.2 Antenna tests

The trial route, being part of a new 6-GHz route, had newly installed antennas between Hillsboro and Richwood and newly installed space-diversity antennas. A series of antenna measurements were made to

characterize the transmission environment for AR6A radio. The measured parameters included section loss (SL), amplitude response, cross-polarization discrimination (XPD), and front-to-back (FB) ratio. In addition, checks for RF interference were made at each receiving antenna. The test results indicated generally good antenna performance; however, one antenna at Cole Camp did have to be reoriented slightly to meet AR6A System requirements. Junction interference from a TH-3 crossing route at Rosati was severe and had the potential to cause an improper sequence of operation of the space-diversity and 500A switching systems. This situation was corrected before the AR6A hop and switch section tests began.

5.5.3 Hop tests

The installation and alignment of the TR bays were performed by AT&T Long Lines technicians and served as a field trial for the initial issue of the BSPs. Radio bay hop tests were then performed jointly by AT&T Long Lines communication technicians and Bell Laboratories personnel. These tests afforded an opportunity to update and refine the hop turn-up BSP. These tests check such parameters as path loss space-diversity switch point, and pilot resupply initiate switch point.

5.5.4 Switch section tests

Switch section tests were performed in three parts. First, those tests necessary to condition a switch section for service were performed. Second, a series of tests were performed to measure the channel performance, and, third, testing was done with TSS-R to verify its performance. Initial switch section testing normally is performed by TSS-R, as discussed in Section 4.9.2. However, at the start of this field trial, TSS-R was not in operation. The same measurements were performed manually as would have been performed by an operational TSS-R System to condition the switch section for service. Performance of the test in this manner served two purposes. First, a database was generated for comparison with initial TSS-R measurements and, second, the latter measured performance of the switch section would determine if the set of TSS-R tests was adequate to condition a channel for service.

The amplitude response of each of the four channels of the switch section from 500A transmitting switch to 500A receiving switch were measured. The results of these tests were then used to compute the number and type of 989-type mop-up equalizers required to equalize the channel to a 0.5 dB flatness. Figure 17 shows a typical radio channel response after amplitude equalization. These tests showed that ordering information for mop-up equalizers did not supply a proper selection of equalizers. New ordering information for the mop-

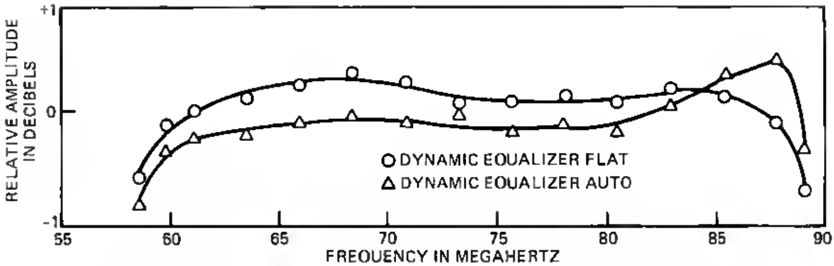


Fig. 17—Typical radio channel response after amplitude equalization.

up equalizers was generated based upon the results of these tests and analysis of factory test data from the initial bays.

The rest of the out-of-service switch section tests listed in Section 4.9.2 were performed on the four channels. The measured tbermal noise was slightly higher than desired. This result was not totally unexpected since some of the initial TWTs had a higher noise figure plus gain sum than specified. This sum (noise figure plus gain) is now used as one of the screening tests for tubes used in systems now operating.

A test of system linearity was of significant importance. Hop and switch section linearity were specified based upon the system model. During the trial, it was found that even though every transmitter met its linearity requirement, some hop and switch section limits were difficult to meet. It was determined that these limits were too stringent because of such variables as hop length, systematic level error, and intermodulation noise contribution from the end hop containing a 500A switch. As a result, new limits for hop and switch section linearity were developed that were more realistic, yet ensured system integrity.

The noise and tone scan performed on each channel showed a few undesired tones in the band, which were identified as originating in the multiplex. These tones are harmonics of carriers and, with production-type filters, are eliminated. With the out-of-service tests completed, noise loading tests began. During this second phase of testing, three types of noise load tests were made. The first type was performed using a test signal generated at basic mastergroup level. Ten basic mastergroups of noise were generated and loaded onto the system at the MGTB. The second type of noise loading was performed by bridging on a live signal obtained at the mastergroup distribution frame. This allowed a comparison of random noise load results with a live signal result. The third type of noise loading used a pseudorandom noise source.[9] These tests were performed to determine (1) the level and type of nonlinearities in the system, and (2) the law of addition, i.e., how these nonlinearities add on a hop-to-hop basis.

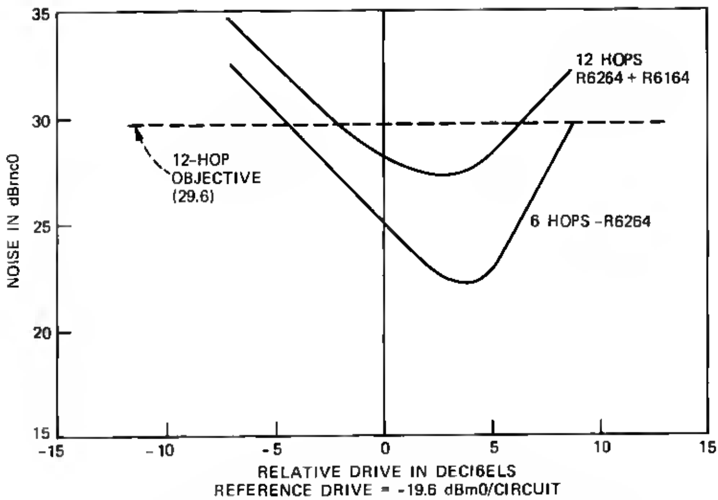


Fig. 18—Noise load tests made during the AR6A field evaluation.

Random noise load measurements were made first on each of the six-bop channels using a random noise load. This measurement was made by looking in a noise slot in each of the ten mastergroups. Figure 18 depicts the results of one such measurement. Measurements were then repeated for a 12-hop switch section by looping back at Windsor first at the 500A, and then at the MGTB employing mastergroup connectors between the transmit and receive MGTB. The results of 6- and 12-hop switch section measurements are shown in Fig. 18. These types of measurements were made early during the field trial, again after several months of operation in whicb no particular effort was made to keep the channel in peak operating condition. They were then repeated near the end of the trial after all transmitters were realigned to ensure their best linearity performance. A hands-off period of two months was then allowed, and tbe noise loading tests were repeated to obtain aging information.

Noise loading was also performed using live signal load before and after the hands-off period. The tests employing a live load used nine mastergroups bridged from the mastergroup distributing frame and one mastergroup of random noise containing the measurement slot. This mastergroup could be placed on any of tbe ten mastergroup positions in the channel. The results showed sligbtly better performance than the random signal, since the average load with a live signal is less than a noise load due to varying talker activity and volume.

Pseudorandom noise loading allowed measurement of IM distortion produced in the channel. These measurements were performed on tbe radio portion of the switch section only, that is, from transmitter "in"

to receiver "out" of the switch section. The test signal was applied at the transmitter "in" on the radio bay at Hillsboro and recovered from the receiving "out" port of the same bay. To complete the circuit, a patch was made at Windsor to loop back the signals between receiver and transmitter. The receiver of the test set measures tbe total IM signal (generated by the 12 radio bays) that falls into a narrow (3-kHz) band. These measurements were made for the expected range of system signal powers to ensure that the IM products were within limits for all operating conditions.

As we discussed in Section 4.6.2, the IM products and their law of addition when a large number of repeaters are connected in tandem is of critical importance. A scheme was derived whereby the law of addition could be determined from a series of pseudorandom noise measurements. To perform these measurements, it was necessary to have personnel present at three stations to perform the patching so that each repeater could be measured individually and tben in combination. The results of the measurements were discussed in Section 4.6.2 with the results shown in Fig. 7.

A period of the trial was devoted to TSS-R testing. During this phase of testing, each of the TSS-R measurements was performed remotely from the Merrimack Valley central computer and then repeated manually on site. This was to ensure that both the proper measurement was being made, that it was being made on the intended unit and, finally, that the results were correct. Maintenance of tbe AR6A System relies upon a combination of SCOTS alarm and radio indications and TSS-R in-service and out-of-service measurements. When a problem occurred on a channel, the indications from SCOTS in conjunction with TSS-R measurements were used to identify the problem and its location, so that maintenance personnel could be dispatched to that location with the necessary equipment and spare parts to effect a repair. As a result of this brief evaluation period, the maintenance scheme was judged viable, but further documentation was necessary for the users to take full advantage of the powerful tools put at their disposal.

During the course of the field trial, several minor problems were uncovered in the functional operation of both radio bays and associated 500A Switching System and the multiplex. Identification of these problems allowed for the necessary circuit changes to be implemented into the product prior to full production.

VI. HOT STANDBY

6.1 System configuration

6.1.1 Repeaters

As we mentioned in Section 1.5, the AR6A hot-standby configura-

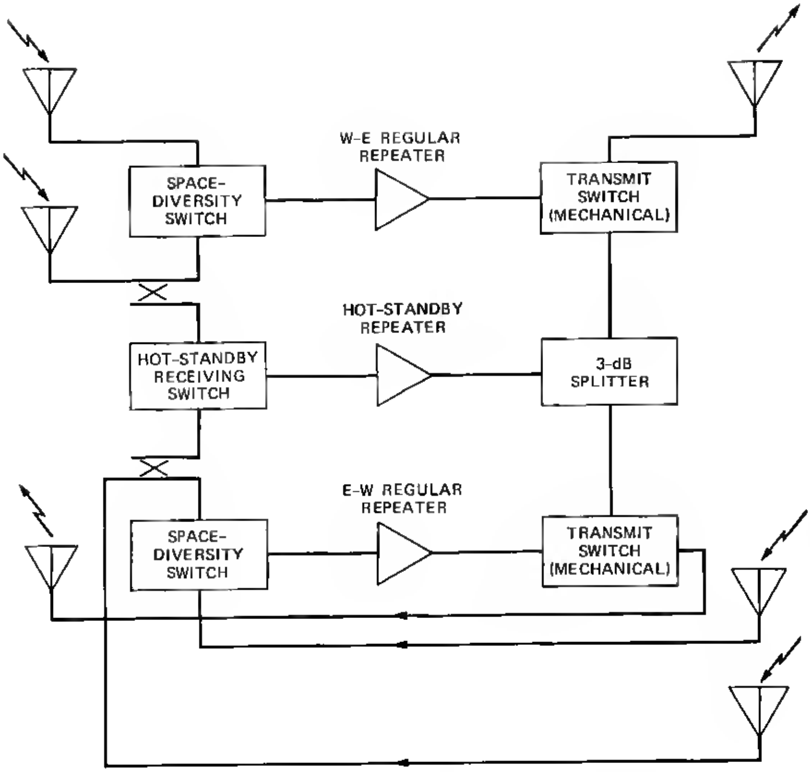


Fig. 19—Hot-standby repeater configuration with space diversity.

tion uses a single hot-standby repeater to protect both directions of transmission. This is illustrated in Fig. 19, which shows a repeater configuration using space diversity.

The primary monitoring function determining whether a TR bay is in satisfactory condition is provided by a broadband power monitor at the transmitter output. Under some trouble conditions associated with high receiver gain, it would be possible for broadband receiver noise to look like a message load, thereby deceiving the power monitor. To avoid this difficulty, high receiver gain operates the pilot resupply switch at the receiver output in the same way as it does in frequency-diversity applications. However, since resupply pilots are not needed for hot standby, the normal pilot input port can be terminated. Thus, when the resupply switch is operated, the transmitter input is automatically terminated, providing the equivalent of a squelch.

Figure 19 shows that in the hot-standby mode the hot-standby receiver does not have space diversity. This eliminates the necessity and complication of transferring the space-diversity control function

between regular and hot-standby bays. The simplification is justified on the grounds that the estimated simultaneity of equipment failure and fading is small enough to be neglected.

The microprocessor-based control unit, in addition to monitoring transmitter power output and other status indicators, arranges the sequence of switch operations during the transfer to or from hot standby. In addition, it provides local and remote status information and supervises local and remote commands with predetermined override priorities. Important considerations relating to the reliability of the 1 × 2 hot-standby configuration are discussed in Section 6.2.

6.1.2 Main stations

Main stations do not lend themselves to a 1 × 2 hot-standby protection arrangement since in general there is only one TR unit per channel at these locations. As a result, main station protection is provided on a one-for-one basis for both transmitters and receivers. A block diagram of the protection arrangement that is integrated with the 501A Protection Switching System is shown in Fig. 20. In essence, the transmitting portion of the 501A System double feeds two transmitters whose outputs are selected by a transmitting switch supervised by a control unit similar to the one used at hot-standby repeaters. On the receive side, receiver selection is performed by the 501A switch on

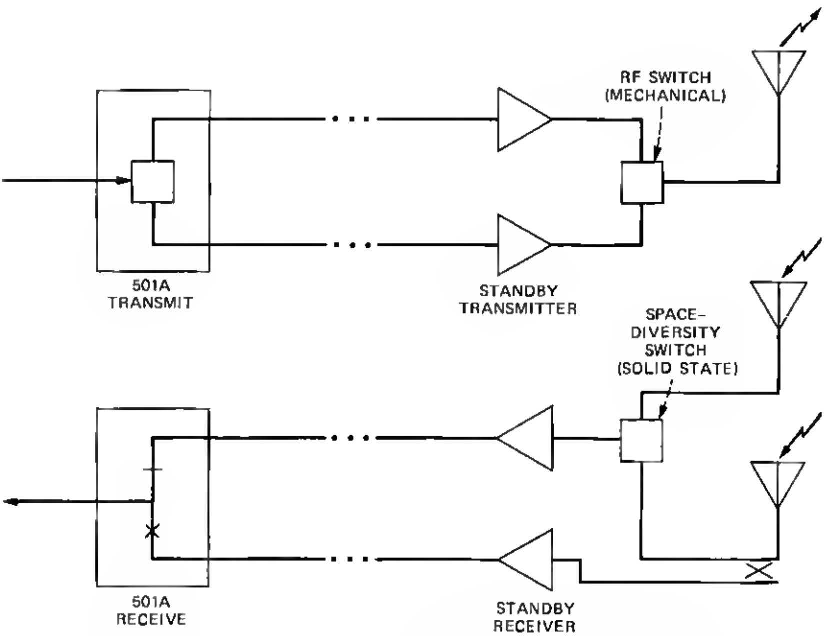


Fig. 20—Hot-standby main station configuration with space diversity.

tbe basis of noise and pilot monitor information identical to that employed on the 500A System.

Interface levels between the 501A System, TR equipment, and multiplex equipment are identical to those employed in the frequency-diversity 500A configuration. Tbis simplifies the conversion from hot standby to frequency diversity wben justified by growth in the route cross section.

6.2 Reliability considerations

The main station 1 × 1 hot-standby configuration follows conventional design practice and will not be discussed in detail. For these systems, the use of high-reliability components and subsystems provide adequate overall equipment reliability.

The outage probability of the repeater station configuration sbown in Fig. 19 can be expressed as

$$P_0 = P_{\mathrm{B}}^3 + 3P_{\mathrm{B}}^2(1 - P_{\mathrm{B}}) + 2P_{\mathrm{S}}P_{\mathrm{a}}(1 - P_{\mathrm{a}})^2 + 3P'_{\mathrm{S}}S_{\mathrm{a}}(1 - P_{\mathrm{a}})^2 + P'_{\mathrm{S}}(1 - P_{\mathrm{a}})^3, \quad (8)$$

where

P_0 = two-way equipment outage probability,

P_{B} = outage probability of a radio bay,

P_{S} = probability of switching system failures that do not cause immediate service outage, and

P'_{S} = probability of switching system failures that cause immediate service outage.

An example of a failure included in P_{S} is a loss of power to the switching system when it is in the normal state with botb regular radio bays operable. The system equipment outage objective results in the requirement that $P_0 \leq 3.21 \times 10^{-7}$. Preliminary calculations showed that, for expected equipment failure rates and a 2.25-hour mean repair time,[12] the sum of the first four terms of eq. (8) would be less than tbe required P_0 with reasonable margin. Preliminary calculations for P'_{S}, however, showed that the last term would be roughly equal to the requirement and special design features would be needed. The probability P'_{S} was reduced by requiring two independent circuits to simultaneously cause the electromecbanical switch shown in Fig. 21 to connect the hot-standby bay to the antenna. Failures in either circuit then cannot cause a loss of service if the opposite direction of transmission is connected to the hot-standby bay input. With this design feature, the equipment outage objective is met for the calculated equipment failure rates.

For hops having space diversity, it was found that in order to meet equipment reliability objectives the space-diversity switch would have

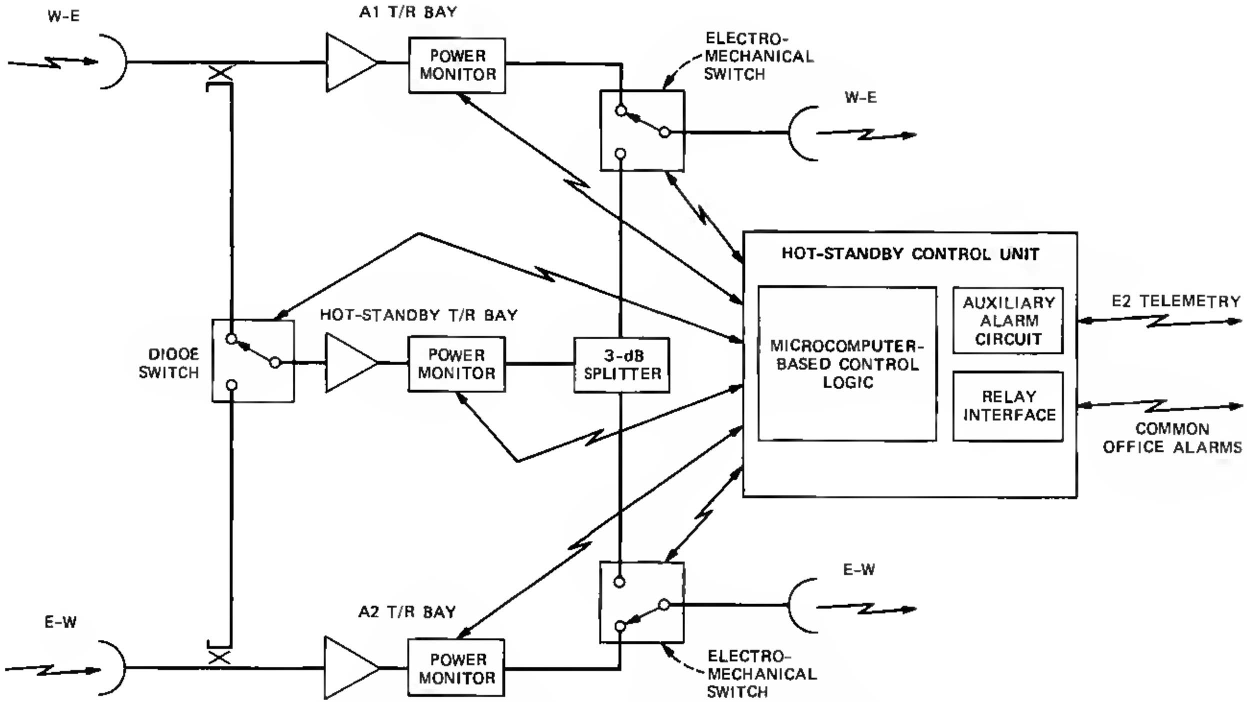


Fig. 21—Block diagram of the 1 × 2 Hot-Standby Protection System.

to be included within the transmission path protected by the standby bay. This leaves the hop without space-diversity protection when the regular radio bay fails but the calculated increase in fading outage is less than 5 percent. The overall reliability of this configuration is better than a design that leaves the switch outside the protected path.

6.3 Switching and control features

A block diagram of the hot-standby switching and control system configuration for repeater stations is shown in Fig. 21. A microcomputer-based control unit is used to control all switching activity and provide equipment checking for alarm purposes. The auxiliary alarm circuit monitors dc power and provides information to the common office alarms. The relay interface conditions the alarm signals for the C1 or E2 telemetry and common office alarm systems.

The hot-standby control unit has three modes of operation: automatic, local, and remote manual. Under normal conditions in the automatic mode, the transmitter electromechanical switches connect the regular (A1 and A2) TR bays to the transmitting antennas. Radio bay failures are detected by the power monitors. A failure of either bay A1 or A2 will cause the system to replace it with the hot-standby bay. For transmitter failures, the loss of signal during switching will normally be less than 15 ms. For receiver failures, the loss will be approximately 50 ms. The standby bay will remain in service until either the regular bay returns to normal or a switch command in the local mode is issued. To revert automatically from the standby bay, the regular bay must be operating correctly for 2 seconds. If another bay should fail when the standby bay is in service, then the appropriate service failure alarm will be set. To prevent unnecessary switching due to failures at a previous repeater, a simultaneous failure of a regular bay and the hot-standby bay is interpreted as an input signal failure and no switching action is taken.

The local mode of operation is provided for maintenance and trouble isolation. The local actions include manual switching of the hot-standby bay to replace either regular bay and a lockout of the standby bay. When the local mode is entered, the pushbutton actions take precedence over switch requests indicated by the power monitors.

If the system is in the automatic mode and the standby bay is idle, the remote manual mode can be enabled by the C1 or E2 telemetry. The remote switching and lockout commands are identical to the local ones. If a service-affecting failure occurs while the system is in the remote mode, a reversion to the automatic mode takes place and the service is protected.

VII. CONCLUSION

The economic attractiveness and efficient spectrum use of the AR6A

System has led to its rapid deployment throughout the United States. The relatively trouble-free introductory experience with this new technology system is a tribute to the many people who contributed to its development. As the authors of this overview article reporting on the work of many colleagues, we wish to acknowledge the contributions of all who participated in the project.

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